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WTCI -32-P

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14 October 2003

Mr. Stuart Dols
National Institute of Standards and Technology
100 Bureau Dr. Stop 8633
Building 226 Room A313
Gaithersburg, MD 20899-8633

Re: World Trade Center Smoke Management Report Files

Dear Stuart:

As requested by Saroj Bohl, I am enclosing for your use a compact disc containing a full copy of the Smoke Management study that Hughes Associates performed for the Port Authority in 1996. Also on the disc are the CONTAM project files of the various base models used in the analysis.

If you have any questions, please contact me at your convenience.

Sincerely,

Lawrence A. McKenna Jr.
Senior Engineer

Copy to:
Saroj Bhol, PANYNJ

Privileged and Confidential

Prepared at the Direction of Counsel

WTCI-327

Smoke Management Evaluation Study of The World Trade Center Complex Excluding the Concourse and Plaza

Draft Final Report

Prepared for

The Port Authority of New York and New Jersey

One World Trade Center

New York, NY 10048

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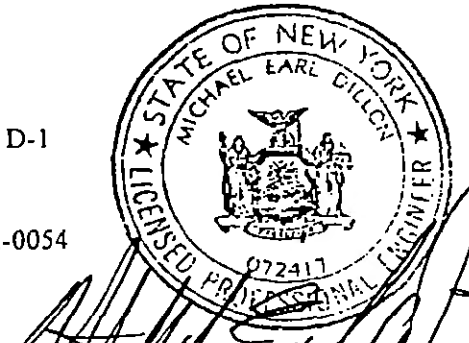

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DRAFT

Executive Summary

This is a report on the Smoke Management Evaluation Study of the World Trade Center Complex, excluding the concourse and plaza levels which were studied under an earlier report (Hughes, 1996).

The evaluation of the smoke management system and the development of alternative smoke management were undertaken as an engineering analysis based on the physics of fire, smoke development, automatic sprinkler response, and smoke flow. Various engineering equations and models were used as described in Section 2 of this report. Major use was made of the mass movement network model CONTAM 96. The model, its validation, and its use in this project are discussed in Section 2 and documented in the several report appendices.

The objectives of this project are to evaluate the existing HVAC and smoke management systems for the four office buildings (WTC 1, 2, 4, and 5) and the sub-grade areas of the WTC complex, and to determine the ability of these systems to perform effectively in the event of a fire or smoke condition. Based on the evaluations conducted, recommendations for future smoke management design are provided.

The criteria followed were based on the protection of the building occupants. from intolerable smoke conditions during the course of a fire and their egress from the building. Conditions were considered to be intolerable in any space where the visibility dropped below 200 ft. or the amount of carbon monoxide (CO) present in the space was sufficient to cause a CO blood saturation (carboxyhemoglobin) level exceeding 12 percent throughout the anticipated exposure time.

The length of time that an occupant can be exposed to the smoke, if present, is a function of the time required for that individual to egress the building, or the space in the building where the smoke is present. In the Towers, the rate of egress is eventually controlled by the exit doors from the stairwells. The maximum rate of flow through such doors is between 50 and 60 persons per minute per door (Nelson and MacLennan, 1995). Based on an expected population of 20,000 persons per tower building, the minimum egress time is about 2 hours to clear the entire building. Given an average population of 200 persons per floor, they can clear the floor and enter the

stairwells in one to three minutes depending on the length of delay in starting evacuation. On this basis the evacuation of three floors to a safe floor below can be accomplished in about ten minutes, depending on the length of time between notification and start of egress.

Based on an expected population of 2,400 in WTC 4, the minimum egress time is about 10 minutes. Similarly, based on an estimated population of 2,600 in WTC 5, the minimum egress time would also be about 10 minutes.

The preceding evacuation time estimates do not include consideration of likely delays in starting egress and various inefficiencies in the use of the exit routes. For design purposes, the estimated actual egress time was assumed to be double the calculated minimum (Nelson and MacLennan, 1995), that is 4 hours for the towers and 20 minutes for 4 WTC and 5 WTC.

Smoke Hazard Potential

This analysis is based on fire safety conditions as they will exist once the program to provide sprinkler protection throughout the entire complex is completed. The provision of sprinkler protection is an ongoing program, currently tied to space renovation and is reportedly between 80 and 90 percent complete in the office buildings.

The current plenum smoke detectors are being replaced with a system of addressable smoke detectors. This will reduce the potential of false alarm and increase the ability to trace the movement of smoke from a fire.
For virtually all fire situations the sprinkler system will control the fire and the smoke can be confined to the space of origin by switching the HVAC system to "Core Pressurization". [1]

The exception of concern is the extremely unlikely but still remotely possible involvement of an entire floor or major portion of a floor in a fully involved fire. The fire used to model this

[1] For the purposes of this study, the term "Core Pressurization" refers to the condition where the core supply fan is on, the toilet exhaust fan is off, the peripheral and inside space supply fans are off, and the interior space return fans are on and set to full exhaust (purge). See Section 4.0

condition is referred to in this report as an "Uncontrolled Fire." Such fires have occurred in other office buildings, and are discussed in greater detail in Section 3.3.2. If such a fire were to occur on any office floor in one of the towers and special smoke control measures were not taken, the results could be disastrous to those in the building involved, spreading potentially lethal smoke through the building faster than the buildings can be evacuated. The potential is most severe in the tower buildings because of the long time required to exit these buildings. (See Section 6.12.)

The source of such an "uncontrolled fire" can be either a fire that occurs on a floor where the sprinkler protection is shutdown or a fire that involves a fuel array that produces a fire of such intensity that it overwhelms the sprinkler protection. The most important safeguards are those that avoid the development of such a fire by tightly controlling and monitoring any shut downs of sprinkler protection and providing special fire suppression or fire resistive enclosures for unusual fuel concentrations, such as track file or other concentrated storage of exposed combustible materials.

Should these safeguards fail and an uncontrolled fire occurs, the building fans can be used to control smoke spread through the buildings and keep the exit paths and other floors in the building clear. The procedure, however, will apply pressures to the stairwell door on the fire floor capable of preventing egress from that floor and should never be initiated until the floor of fire origin is clear of all occupants and the fire has broken out of at least one window. This approach is discussed in greater detail in Section 6.4.1.
A similar but lesser potential for disaster exists if an uncontrolled fire were to occur in 4 WTC or 5 WTC. Here, the shorter egress time lessens the potential. A recommendation is included, however, to consider providing smoke control for the stairwells in these buildings using dedicated fans.

In the event of an uncontrolled fire in 5 WTC under adverse conditions where a wind blew directly into the building through windows broken out by the fire, smoke could be driven throughout the Concourse. A similar fire in 4 WTC could result in a lesser smoke migration into the southeast portions of the Concourse. In the remote event of such a fire, smoke could be held out of the Concourse using the Concourse and tower fans as discussed in this report.

As a result of the analyses conducted, the following conclusions are drawn:

1. Sprinkler Protection

The analysis in this project along with those in the previous project, Smoke Management Evaluation Study of The World Trade Center Concourse and Plaza (Hughes, 1996) show that, with the several exceptions noted herein, the provision of sprinkler protection will allow only minor smoke migration from the space of fire origin. All of these analyses of sprinklered fires indicate that exit paths, stairs and elevators will remain sufficiently free of smoke to be safely used for building egress. In these cases, persons proximate to the fire may have to evacuate the space of fire involvement but can find safe refuge in the core area or on an adjacent floor.

2. Stairwell Protection in Towers

As discussed in Section 6.5.1, the height of the towers and the tower stairwells precludes effective traditional stair pressurization of major portions of the stairs by air injection. The protection of the stairs from smoke intrusion can be accomplished, however, by core pressurization in the expected cases and by positive pressure ventilation in the unlikely event of an uncontrolled fire. See Section 6.4.

3. Core Pressurization Smoke Control in Towers

The vast majority of anticipated fires in the towers will be small and controlled by the sprinkler system. In these cases, setting the HVAC systems to the Core Pressurization configuration (See Figure 6) will contain the smoke in the area of fire origin, and prevent the spread of dangerous levels of smoke and contaminants into the core, the stairwells, and the elevator shafts.

4. Positive Pressure Ventilation of Towers

As noted in the analysis, it is possible to hypothesize a fire of major magnitude that could involve an entire floor in one of the Towers. Such fires have occurred in office buildings without sprinkler protection, but to date we are unaware of any that have occurred in a sprinkler protected office facility. A fire involving an entire floor was used in this study to assess the potential of developing smoke management systems capable of withstanding the most severe exposure.

In the unlikely event that an uncontrolled fire develops, it is possible to use the HVAC fans to provide smoke control for the tower buildings, once that fire breaks out windows. The approach involves positive pressure ventilation[2]. (See Figure 7) This approach as described in Section 6.4.1 is designed to keep both stairwells and elevators clear of smoke and toxic gases. The use of these fans under these conditions can result in pressures on the fire floor stairwell doors that would prevent any persons still on that floor from escaping. It should never be used until that floor is clear of occupants, and only under the direction of the fire officer in charge of the incident.

5. Stairwell Smoke Control, 4WTC

In 4 WTC it is possible to use air flow, either provided by dedicated fans or diverted into the stairwell from the building system, to pressurize the stairwells sufficiently to exclude smoke from the severe winter fire condition described above. This can be accomplished while not over-pressurizing the stairs.

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[2] For the purposes of this study, the term "Positive Pressure Ventilation" refers to the condition where all supply fans are on, all toilet exhausts are off, and the only return fans that are operating (on exhaust mode) are those serving the HVAC zone where the fire occurs.

6. Stairwell Smoke Control, 5 WTC

In 5 WTC is possible to use air flow as in 4 WTC to pressurize the stairwells. However, the air flow needed to provide for pressurization with up to 3 doors open can over-pressurize the doors when all of the doors are closed. For such a system to work in 5 WTC, it will be necessary to provide a nearly instantaneous pressure control device, such as barometric dampers. This is necessary to assure sufficient pressure when doors are open and prevent over pressurization when all doors are closed.

7. Smoke Control for Elevators, 4 WTC and 5 WTC

In both 4 WTC and 5 WTC there are vestibules outside the entrances to the freight elevators on each of the office floors. Simulations using air flow to pressurize these vestibules indicated that it is feasible to use air injection into these spaces to provide "areas or refuge" for handicapped individuals to be removed from the building via these elevators. In 5 WTC, the model indicates that it is necessary to inject 4,000 cfm into the vestibule on each floor. In 4 WTC, the model indicates that it is necessary to inject 3,000 cfm into the vestibule on each floor.

8. Smoke Flow into Concourse

If the hypothesized severe winter fire occurs in 5 WTC, the analysis indicates that the smoke will spill out of that building into the Concourse and across the Concourse into the tower buildings. The analysis indicates that this flow can be restrained if one of the following options is employed:

a) The entire concourse and the towers are placed in a pressurization mode by shutting off the return and exhaust fans serving the Concourse and a sufficient number of return fans in the Towers to prevent flow from the Concourse into the Towers, or

b) Install doors that will be closed at the time of a fire to separate the Concourse and Plaza level entrances from 5 WTC to the Concourse, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8, or

c) Install doors that will be closed at the time of a fire on the escalator, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8.

Option (a) will confine the smoke to the floor of origin, keeping the exit routes clear throughout the fire. Options (b) and (c) will permit smoke migration into the lobbies on all floors below the fire floor, with some migration into the adjacent area of the Concourse, but the exit routes will remain clear.

9. Fire in PATH Terminal

A minor, sprinkler controlled, fire in the PATH terminal would result in local smoke and minor spread to those portions of the Concourse nearest the PATH entrance. In case of a major fire in the PATH terminal, without either sprinkler suppression or smoke control, smoke would spread widely over the entire Concourse and into the tower buildings. To prevent this it would be necessary for the entire Concourse to be placed in a pressurization mode, by shutting down return and exhaust fans serving the Concourse and adjusting the fans in the towers to prevent air flow from the Concourse into the towers. If this were done, however, the smoke from the fire would be forced into the PATH terminal and system.

10. Truck Fire at Loading Dock

If a fire develops in the cargo compartment of a large truck, shielded from the garage sprinkler protection, a serious condition of smoke migration into the adjacent tower can occur. With the combination of open loading dock doors and no smoke control in the tower, smoke can spread into the B-1 level. With the loading dock doors closed and the sub-grade levels and the lobby return fans off, smoke can be controlled, even on a severe winter day. The loading dock doors should be kept closed, or arranged to close automatically, in the event of a fire.

11. Tower Lobby Fire

The lobby HVAC system has the capabilities to be used as an atrium smoke control system to keep the exits through the lobby of a tower passable given a large (11,000 Btu/s) fire in the lobby. Under severe winter conditions it would be necessary to

shut down sufficient supply fans in adjacent zones to prevent stack effect flows up the elevators from diverting smoke into the elevator shafts.

12. Passenger Car Fire in Garages

A fire involving a passenger car in the garage would not result in significant smoke migration into the adjacent buildings or obstruct egress from the garages.

13. Impact of Shutting Down Fans Upon Smoke Detection

Shutting down fans on smoke detection is less effective in terms of smoke control than leaving the fans on and spilling all of the return and setting the supply on 100% outside air.

14. Interrelationship of All Elements of WTC Complex

The analyses in this project re-enforce the fact that all of the HVAC systems in the entire complex interact significantly. Any major changes in one portion of the facility may impact other portions of the facility, potentially affecting the movement of smoke from a fire. The most significant impact is that produced by the PATH system on the Concourse and 5 WTC. Other impact could result if separate sections of the complex, such as one or more office building, were placed under separate HVAC management from the complex as an entity.

The report makes the following recommendations to the Port Authority, based on the analyses conducted and the conclusions drawn:

1. Sprinkler Protection (Entire Complex)

Complete the program for total automatic sprinkler protection of the entire complex. Where spaces are known to be used for storage or track files or other high concentrations of potential fuel for a fire, provide extra protection in the form of additional suppression capabilities (i.e. increased discharge density from the sprinkler system), fire resistive enclosure of the space involved, or both.

2. Emergency Smoke Management Sequence in Tower Buildings

The following sequence of actions is recommended in case of a fire in one of the towers.

a) Notify the NY City Fire Department and follow the WTC emergency procedures for the floor involved and adjacent floors.

b) Upon activation of any smoke detector or sprinkler system, set the HVAC system covering the entire zone where the fire is detected to core pressurization.

c) If smoke detectors involving 2 or more detectors on floors other than the fire floor occurs, evacuate all floors served by the MER serving the fire floor that are on the same side of the MER floor as the fire floor; that is all floors served by the same supply fans that serve the floor of fire involvement.

3. Handling An Uncontrolled Fire in A Tower

While an uncontrolled fire is an unlikely event, it is prudent to provide contingency plans for smoke protected egress and refuge in case of such an event occurs. Plans to institute positive pressure ventilation as described in Section 6.4.1 should be developed and coordinated with the New York City Fire Department and regularly rehearsed and tested. Implementation of positive pressure ventilation by its nature is a fire ground action and would be implemented under the direction of the fire officer in charge with advice and assistance from the WTC engineers.

4. Smoke Control for Stairs and Elevators, 4 WTC and 5 WTC

It is recommended that pressurized smoke control be considered for the stairs and the freight elevator vestibules in 4 WTC and 5 WTC. (i.e., a dedicated fan system injecting air at multiple points in the stairs and into the vestibules each floor.) As discussed in the analysis, barometric relief or other pressure relief will be needed in the stairs for 5 WTC. The recommended operating sequence is to initiate the Stair and vestibule pressurization upon activation of more than one detection of smoke in the plenum space. To lessen the circulation of smoke through the HVAC ducts, the HVAC system should not be shut down but set to total outside air with no recirculation.

5. Additional Area of Refuge Design Elements, 4 WTC and 5 WTC

The pressurization of the freight elevator vestibules is intended to provide the basis for "areas of refuge" for handicapped persons. If the Port Authority elects to use these vestibules for this purpose it will be necessary to:

a) Equip all of the vestibule doors with door closers triggered by the activation of the smoke control system.

b) Provide the necessary signage and communications system to identify the spaces as areas of refuge and enable anyone in the areas of refuge to communicate their location and needs to the WTC emergency control location.

c) Recall the elevators serving the vestibules to the exit floor and place them in emergency service. The accessible egress paths usable by a mobility impaired person is via the elevators serving these vestibules exiting at the Concourse or B-2 levels. Both of these routes are potentially exposed to blockage by smoke, though the likelihood of both being blocked is improbable, as demonstrated by the analysis in this report. For this reason it will be necessary to know the condition of the egress routes before evacuating anyone using the elevators. Evacuation should then be controlled by an emergency operator who is aware of any smoke in the exit routes and can act accordingly.

6. Keeping Smoke Confined to 5 WTC

A special problem exists in case of a severe fire in 5 WTC. If, in event of fire, the smoke detectors indicate smoke in three or more smoke detection zones, it is possible that a fire overtaxing the sprinkler system has occurred. In this case there is a danger of smoke spreading into the Concourse and tower buildings. To counter this, if such a warning occurs, all of the returns from the Concourse HVAC systems should be shut down. If such a fire occurs under winter conditions, return fans in the towers will also have to be shut down to keep smoke within the perimeter of 5 WTC. Other approaches to controlling the smoke from a fire in this building were modeled (See Section 6.4.2), but none exhibited the same level of safety in 5 WTC and the Concourse open to it.

7. PATH Terminal

The Port Authority needs to continue its studies of smoke management in the PATH terminal. A minor, sprinkler controlled fire in the terminal would not present a serious hazard. A major fire, typified by a PATH car fire could, however, expel smoke into the Concourse, migrating either into the towers or into 5 WTC. The smoke could be held back by shutting down all Concourse return fans and sufficient return fans in the towers so that air flow is from the tower lobbies into the Concourse. If this were done, however, the smoke would be forced into the terminal and the PATH system itself. We understand that Port Authority Engineering has completed a preliminary design for the PATH Terminal smoke management system that is compatible with the criteria, assumptions, and findings of this study.

8. Interrelationship of PATH Terminal and Complex

It is important, however, that no solution that involves the closure of the PATH terminal from the Concourse be considered without evaluation of the effect of that closure on smoke movement in the Concourse. The PATH terminal is a major source of air that avoids a winter condition where the towers could impose a negative force on 4 WTC and 5 WTC.

9. Loading Dock Smoke Control

Damage to the doors between the loading dock and the tower building should be repaired. The rolling steel doors should be equipped with smoke detectors, arranged to close these doors if they should be open and a fire occurs at the dock. Additionally, if two or more smoke detectors in the return air from the B-1 space are activated, the supply to the sub-grade portions of the tower involved and the supply to the lobby of that tower should be shut down.

10. Tower Lobby Smoke Control

In case of fire in the lobby of one of the towers, the lobby supply and return should be continued in operation with no recirculation and 100% fresh air supply and 100% exhaust of the return. In winter conditions the core returns for floors 1 to 6 and sub-grade areas should be shut down. Additional returns should be shut down until any flow from the concourse or outside into the lobby is mitigated. To implement this it is recommended that a pressure sensors be installed in each of the tower lobbies that measure the pressure difference between

the lobby and the Concourse and between the lobby and the exterior. The data from these reading should be shown in the control room.

11. Further Tests

Tests of the proposed procedures should be conducted under both summer and winter extreme conditions prior to implementation of this study to verify the pressures predicted by the model. The procedures recommended above are based on calculations using the model CONTAM96. As such they involve the use of selected field measurements and assumptions relative to specific leakage paths and dimensions. It is felt that pressure differentials and pressures applied to doors in the means of egress are the key measurements. The use of smoke tracers, while not considered essential, could be of assistance in discovering unanticipated leakage paths.

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1.0 Introduction

This is a report on the Smoke Management Evaluation Study of the World Trade Center Complex, excluding the concourse and plaza levels, which were studied under an earlier report (Hughes, 1996). The report is divided into the following Sections:

1. Introduction
2. Tenability
3. Fire Scenarios
4. Smoke Control Modes
5. CONTAM 96 Network Model
6. Studies Based on Smoke Control Cases
7. Conclusions
8. Recommendations
9. References
10. Appendices
    - Appendix A: CONTAM 96 Theory and Validation
    - Appendix B: World Trade Center CONTAM 96 Models
    - Appendix C: Interim Report
    - Appendix D: Wind Pressure Profiles.
    - Appendix E. Simulations

The World Trade Center complex considered in this study contains two 110 story towers (1 and 2 WTC), two 9 story buildings (5 WTC and 4 WTC), and interconnecting basements and concourse. The Concourse and a proposed enclosed Plaza were considered during the earlier study (Hughes, 1996), and were included in this evaluation only to the extent that they were important to the studies being conducted. The boundary conditions at the PATH terminal, the NYC Subway entrances, the Hotel, and the Customs House developed during the earlier study (Hughes, 1996) were included in the models constructed for this study.

The evaluation of the smoke management system and the development of alternative proposals was undertaken as an engineering analysis based on the physics of fire, smoke development,

automatic sprinkler response, and smoke flow. Various engineering equations and models were used as described in Section 2 of this report. Major use was made of the mass movement network model CONTAM 96. The model, its validation, and its use in this project are discussed in Section 2 and documented in the several report appendices.

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2.0 Tenability

2.1 General

The design criteria used in this study are based on a determination of the distribution and extent of conditions that would cause harm to persons in the spaces, or which would obstruct evacuation. The principal tool used for this analysis was the network model CONTAM 96. This model is discussed in detail later in this report. In addition, analysis was made of the vision distance and CO contamination. It was assumed that conditions would be unacceptable if the vision distance was less than 200 ft., or if the CO concentration would result in a carboxyhemoglobin (COHb) level exceeding 12% in exposed individuals during the course of the fire.

Representative design fires were developed using existing test data and experience. Door opening forces were considered to be excessive if the opening force exceeded 30 lbs. (See Section 6.7 for the calculation method used.)

2.2 Environmental Conditions

For the CONTAM 96 simulation, it was assumed that the internal temperature in the complex was 70°F. For the cases involving an uncontrolled fire (Section 3.3.2), it was assumed that the temperature in the space of fire involvement was 2,000°F. Exterior conditions were varied. In most cases either a severe (windy) winter day or a still summer day were simulated.

Winter conditions were simulated as an outside temperature of 15°F and a westerly wind with wind speed varied with height above grade. The wind speed is profiled in Appendix D.

The conditions simulated varied from approximately 10 mph at grade to 60 mph across the top of the 110 story towers. Summer conditions were simulated at an outside temperature of 90°F and no wind.

To study the impact of wind versus temperature, a few cases were run with the outside temperature set at 15°F with no wind and with outside temperature set at 70°F with the same westerly wind as simulated for winter conditions.

2.3 Vision Distance

Vision distance was calculated using the vision mass product density relationships reported in FPETOOL (Nelson, 1990). The equation used is:

$$V_e = \frac{3}{e_s M_p} \qquad \text{Equation 1}$$

where:

V_e = Distance in meters at which there is approximately a 95% reduction in light transmission. (At this level of light an illuminated exit sign can be seen.),

e_s = Specific extinction coefficient. (m^2/g) A value of 0.1 m^2/g was used for the office, uncontrolled (total floor burn out), truck, and kiosk fires in this analysis. This is a reasonable representation of the smoke obscuring properties of a free burning mix of common materials as found in these areas. A value of 0.5 m^2/g was used for the car fire due to the high concentration of polymers which produce smoke with distinctly different obscuration properties. (Tewerson, 1988, and Mulholland, 1995)

M_p = Mass of fuel burned per unit volume as a concentration in the space under evaluation.

2.4 CO Exposure

Exposure to CO was modeled as carboxyhemoglobin (COHb) uptake based on Stewart's equation as reported by Purser (1995).

The equation used is:

$$\%COHb = \left(3.317 \times 10^{-5}\right)\left(ppm.CO\right)^{1.036}(RMV)(t) \quad \text{Equation 2}$$

where:

%COHb = The percent carboxyhemoglobin accumulated in the blood stream of a person exposed to the indicated Level of CO for time *t*.

ppm CO = CO concentration in parts per million

RMV = Volume of air breathed (L/min)

t = exposure time (min)

A base value of 18 L/min was assumed for the RMV, since it is a typical breathing rate for an active person. This can be as much as twice the rate for a person at rest (e.g., typical resting respiration rate is 9 L/min) and half the rate for a person under heavy physical stress (e.g., 36 L/min).

The % COHb is a measurement of the extent that carboxyhemoglobin has replaced oxyhemoglobin in the blood, and is the basis of harm from CO exposure. In general, a normal adult will be incapacitated if the COHb level approaches 30%, and may die if it approaches 50%. Given that an individual's susceptibility is very dependent on their physical condition, and that it has been demonstrated that negative effects on human psychomotor performance do not begin to occur until COHb levels exceed 12%, the tenability criteria for this study was set at 12% COHb. (Purser, 1995)

3.0 Fire Scenarios

The development of representative fire scenarios involves development of design fires, the design fire location within the complex, seasonal weather variations, HVAC system variations, building variations, and candidate smoke control variations. Table 3.1 provides a summary of the fire

scenarios used in this study. The investigation involved numerous permutations of these to analyze the potential fire scenarios and candidate smoke control systems.

1. In the tower, the fire locations were selected based on the HVAC system layout. Floors were chosen in both the upper and lower sections of HVAC zones to evaluate the effectiveness of the control strategies. Floors at low, mid, and high elevations were chosen to evaluate the impact of stack and wind effects.

2. Since concise data on the presence of open interior stairs (tenant stairs) are not available, some simulations were run where the stairs are located in floor openings that breach the HVAC zones.

3. The impact of a work station fire in the tenant space on the upper sky lobby, Floor 78, was assessed. The sky lobby floors observed during the site visit are extensively subdivided into tenant various tenant spaces, which make an effective barrier to fire spread. The uncontrolled fire involving the entire floor was not considered a potential on this floor.

Table 3.1 Summary of Fire Scenarios

Building	Fire Scenarios
WTC Towers 1 and 2	office workstation, uncontrolled fire, car in garage, truck at loading dock, kiosk in atrium, and kiosk in concourse.
WTC 4 and 5	office workstation, uncontrolled fire, and truck at loading dock.
Path Terminal	kiosk at newsstand level, and a 20MW fire used for a trace contaminant source
Sub-grade Levels	car in garage, and truck at loading dock

3.1 Discussion

Based on tours of the complex and experience, five design fires were selected that represent conservative but reasonable estimates of fires that may occur in the World Trade Center complex: an office workstation, an uncontrolled fire, an automobile, a truck, and a kiosk. Each of these are discussed in greater detail below.

3.2 Assumptions

For all cases where the HVAC fans are operating, it is assumed that the electrical power supply to the fans continues to be available throughout the fire.

Unless specified otherwise each of the scenarios incorporated the following assumptions about the sprinkler protection:

1. The entire fire area is protected by an automatic sprinkler system.
2. The sprinklers are standard heads rated at 165°F,
3. The initial flow out of the first heads operating will be 0.2 gpm/ft^2, and
4. The sprinkler design criteria is 0.10 gpm/ft^2 over the most remote 1,500 ft^2 in office areas, and 0.16 gpm/ft^2 in storage and below grade areas.

For each of the scenarios, it is assumed that the fire is not detected until the first sprinkler or plenum smoke detector activates. It is expected that the sprinkler system will not extinguish all of the fires. For those fires that will not be extinguished by the sprinkler system, the fire's life (i.e., the time during which smoke continues to be produced) was determined by estimating the alarm transmittal and fire department response time.

In estimating these times, it was assumed that the water flow or smoke detection alarm is transmitted to the fire department within 3 minutes, and that the fire department alarm and response time will average an additional 10 min. from receipt of the alarm to arrival at the site. Allowing 10 min. for the fire department to arrive on the fire floor, locate the seat of the

remaining small fire, and to extinguish that fire, a total of 23 minutes have elapsed from initial alarm to extinguishment. This time will be added to the time to first sprinkler activation, which is described under each scenario, to arrive at the total time of fire life for each case. The uncontrolled fire was modeled as though the fire department was unable to control it until the fire essentially burned itself out.

3.3 Fire Scenarios

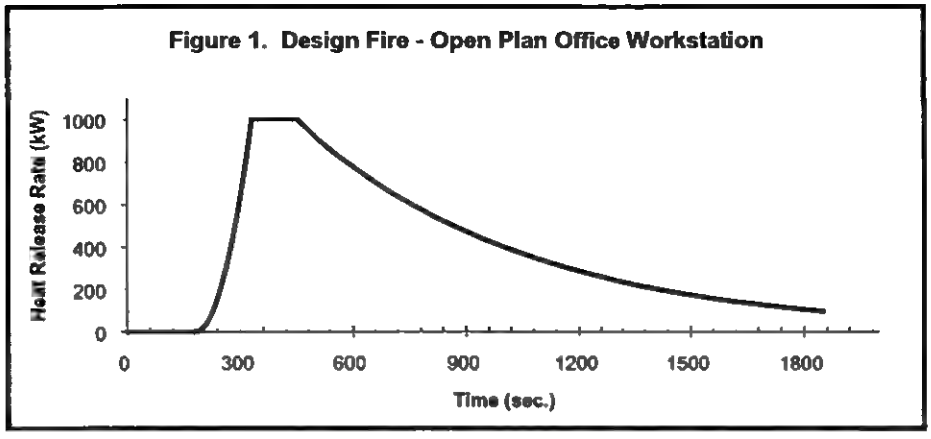
3.3.1 Work Station

Recent work by at NIST (Madrzykowski 1992) and at the National Research Council - Canada (Lougheed 1996) has assessed the fire potential of open plan office workstations. Full scale fire tests were conducted in both efforts.

While there are differences between the data reported, they are not substantial, and appear to be largely due to differences in the workstations tested and the fuels placed under the horizontal surfaces of the stations. Combustible fuels located under these surfaces will be shielded from the water spray from a sprinkler. Since the sprinkler may not be able to extinguish these fires, they are assumed to continue to burn, at a reduced rate, until manually extinguished.

The design fire curve to be used is that proposed by Lougheed (1996). This curve was generated by plotting the results of seven full scale tests and drawing a curve that encompasses all seven of the test curves, overestimating each of the individual tests. This provides a conservative estimate for the design fire. Figure 1 shows the heat release rate curve of the workstation fire that was used in this study.

The curve proposed by Lougheed represents a more severe fire than is indicated by the Madrzykowski work due to differences in the design of the workstations tested, and due to the heavy fuel loading placed in the concealed areas under the desks and tables. Lougheed's tests were conducted on workstations that appear to be similar to the most severe cases observed in the World Trade Center complex during site visits and surveys.



Given the selection of this design curve, the next question is to determine the point on the curve at which the fire is extinguished, and smoke production ceases. In Lougheed's seven tests, the first sprinkler activated at between 3:46 min. and 5:40 min. after ignition. For this analysis a conservative estimate of 6:00 min. for time to activation of the first sprinkler is adopted. Adding this to the 23 minutes from initial alarm to extinguishment (See *Assumptions*, Section 3.2) yields a fire life time of 29 min. A 30 minute burn time was used in this analysis.

3.3.2 Uncontrolled Fire

There is a potential of a fuel load in on office area that exceeds the capacity of the sprinkler system. Testing by Lougheed, et. al. demonstrates that mobile shelving units can overtax standard light hazard sprinkler system designs (Lougheed, 1994). While modifications to the sprinkler design and flow rates can help to alleviate this problem, it is reasonable to expect that similar conditions may exist somewhere in the complex.

Mobile shelving units represent one of the most challenging office occupancy fuel packages from a fire suppression point of view since much of the fuel load is located under metal shelves that are packed tightly together. The heavy concentration of combustible materials and the shielded configuration combine to create a situation where the typical "Light Hazard" sprinkler system

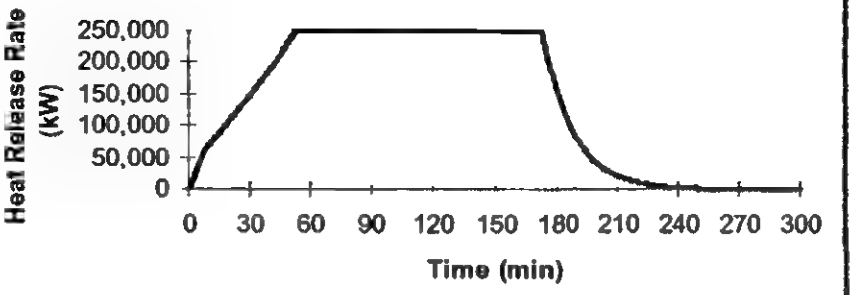
design that is the standard design in the complex can be inadequate to suppress, or even to contain, the fire. This is a realistic scenario to model the case where the sprinkler system is overtaxed by the fire, or for when a sprinkler system is turned off for any reason. Nearly any other collection of high piled combustible storage should produce the same results—a total floor burned out.

This fire was modeled after those that occurred at the First Interstate Bank in Los Angeles (Nelson, 1989), and the 1 Meridian Place fire in Philadelphia. (Klem, 1991) In each of these fires, a localized fire grew to flashover and spread to adjoining spaces on the floor. These in turn grew to flash over, and spread the fire farther along the floor. This sequential spread continued until the entire floor was fully involved, a process that took 30 minutes to an hour. During that time, most of the windows broke out and the fire also spread to floors above via interior and exterior routes.

A fire spreading beyond the sprinkler design area, or one which exceeds the capability of the system to suppress will open more and more sprinklers, resulting in a significant decrease in the quantity of water discharged from each head, to the point where the sprinklers are completely ineffective. It is assumed that the fire will not spread vertically to the floor above, since sprinklers operating on the floor above such serious fires have been shown to prevent this type of fire spread. (Klem, 1991)

A uniform fuel loading of 12 lbs/ft^2 (Caro, 1995) is assumed, for a total of 360,000 lbs on the floor. Also assumed is an average heat of combustion of 15 kJ/kg. The design fire shown in Figure 2 was used, based on analysis of previous fires of this magnitude. (Nelson, 1989) This fire grows to 60,000 kW in 7.5 minutes, and then increases every 15 minutes by 60,000 kW, simulating involvement and flashover of additional floor areas. After reaching 250,000 kW, the fire burns at that rate for 2 hours, and then decays for 2 more hours. The total mass loss under this design curve is 160,000 kg (352,000 lb).

Figure 2. Design Fire - Uncontrolled Fire



3.3.3 Automobile

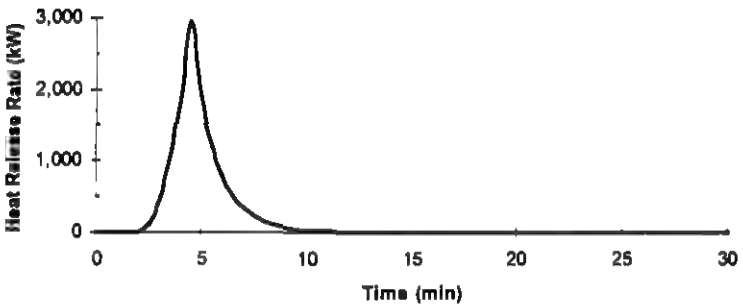
Fire tests on automobiles have been conducted by a number of researchers. Due to variances in the test protocols and data recorded in each of the efforts, there is considerable divergence between the results reported. This appears explainable by the differences in instrumentation, vehicles tested, and the ignition scenarios used.

Mangs (1994) and Shipp (1995) reported heat release rate (HRR) from their tests, which were conducted without automatic sprinkler coverage. Mangs' tests produced peak HRR ranging from 1.5 to 1.9 MW, while Shipp reported HRR of 4.3 and 8.7 MW. Australian tests (BHP, 1987) did not report HRR, but instead reported air and structural element temperatures above and around the fire. The BHP work clearly illustrates the effectiveness of automatic sprinklers in controlling vehicle fires. The ECCS produced an extensive review of the work by Mangs and BHP (ECCS, 1993), although it focuses on the unsprinklered work by Mangs, and draws conclusions based on an unsprinklered parking garage.

This scenario assumes that the sprinklers are present and operable, and the design fire is based on this assumption. The design curve shown in Figure 3 shows the heat release rate curve for this scenario. This curve was generated by plotting the three vehicle fires reported by Mangs and the two fires reported by Shipp together and generating a "design" fire curve that encompasses all of the five fires. This curve was then input into the Detact model found in FPETOOL (Nelson, 1990) and was used to estimate the sprinkler activation time of 276 seconds, based on a ceiling

height of 10 ft and 10 ft, by 10 ft spacing of sprinkler heads. It is assumed that the fire growth stops at sprinkler operation, and that the fire begins to decay at that time, as was show by BHP (1987). The peak heat release rate was determined from the unsprinklered "design" fire curve at the calculated sprinkler activation time.

Figure 3. Design Fire - Car



The decay portion of the curve was developed by estimating the mass lost in garage vehicle fires under operating sprinkler systems, as reported by BHP (1987). This report provided estimates of the quantity of interior fuels unburned following extinguishment, which ranged from 30% to 50% of the total. The EC report estimates the energy content in the heat release rate curve for each of the four major fuel packages in a vehicle: the passenger cabin, the engine and front tires, the trunk and rear tires, and the fuel. The passenger cabin contains the largest fuel package in a car, reported as 47%, or 1.89GJ. Assuming an average heat of combustion of the materials in an ordinary car is 15MJ/kg (7,000 Btu/lb), the estimated mass of combustibles present is 47 kg (104 lb). Taking a conservative estimate of 50% of this fuel is unburned, based on BHP, gives an estimate of 23.5 kg (52 lb) of material will be burned in the design fire. The mass loss was estimated as a function of the heat release rate, and a decay curve was constructed so that the area under the corresponding mass loss curve resulted in a total of 23.5 kg mass loss. The time of decay was based on analysis of the air temperature data reported by BHP.

A comparison of this curve against those reported by BHP, which reported only air temperature, and not rate of heat release, shows a general correlation. BHP reported on four test fires conducted under automatic sprinklers. In each case the fire was easily controlled, with the sprinklers operating at between 37 sec and 4:10 after ignition. The sprinklers cooled the fires quickly, as shown by the rapid reported temperature decreases.

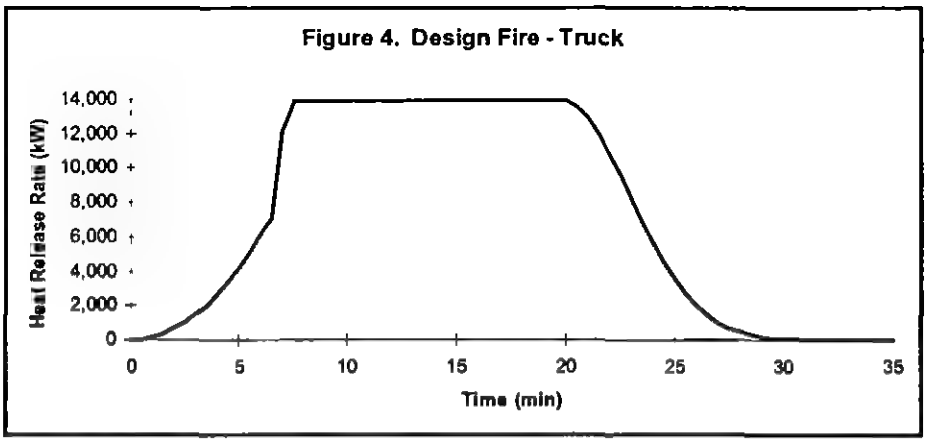
In this case, as in prior scenarios, burning time was used to estimate the quantity of smoke, CO and CO_2 released during the fire. A 30 minute simulation time for the auto fire was used.

3.3.4 Truck Fire

This fire was selected since it represents a severe smoke generation condition. A fire inside a truck at a loading dock will be shielded from the sprinkler system until the truck body collapses, so the sprinkler system will be largely ineffective in controlling smoke production. A fire in truck would be ventilation limited, and thus produce large quantities of unburned soot and CO. Since the fire would be shielded from the sprinkler, it will continue to burn until the fire department effects manual suppression. It was assumed that the plume extending out of the open door will activate the sprinklers, which would cool the roof of the truck, delaying collapse. It was further assumed that the sprinkler operation will affect the combustion chemistry in the plume, and that continuing combustion in the region of the plume will be severely constrained by the cooling effects of the sprinkler operation. As a result of this effect, it was assumed that the CO production rate of this fire is ten times that of the other design fires in this study (Nelson, 1989).

The model FIRE SIMULATOR from the FPETOOL (Nelson, 1990) collection was used to estimate the initial and maximum growth rate. It was assumed that the initial fire developed as a fast t-squared fire (i.e., 0.044 times the square of the elapsed time in seconds) until flashover inside the cargo compartment. At that point, the maximum rate of heat release was controlled by the amount of air available through the open doors of the cargo compartment (i.e., assumed to be 8.5 ft high and 11 ft wide). FIRE SIMULATOR indicated a rate of heat release of about 13,000 kW, which was rounded up to 14,000 kW for this analysis.

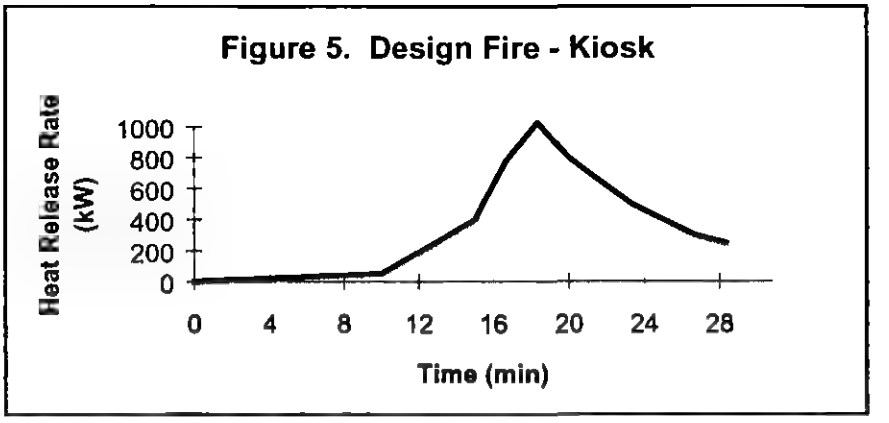
The design curve shown in Figure 4 shows a fast developing fire inside a truck that has a lining of 1/2 inch plywood on the interior walls and top. The fuel load inside the truck is estimated at 50 lbs/ft^2. The curve assumes fire department operation starts at 20 minutes, and total extinguishment 15 minutes later.



3.3.5 Kiosk Fire

The National Institute of Standards and Technology (NIST) has recently conducted tests of kiosks that are similar to the push carts used in the concourse and the commercial displays observed on the Mezzanine Level of the towers. The kiosks tested were slightly less than 4 ft by 4 ft in plan and 6 ft 9 in tall. The kiosks were loaded with hanging tee shirts in the upper display area and tee shirts in cartons in the cabinet space under the sales area. The burning rates of the kiosks tested are reasonable similar to the burning rates expected from the push carts and displays observed in the World Trade Center during the site visit. Figure 5 shows a plot of the average heat release rate from several kiosk tests.

This scenario was used in the prior study on the Concourse and Plaza levels of the complex. The fire model, the sprinkler model, and the CO and CO_2 generation models used in the previous study (Hughes, 1996) were used in this study.



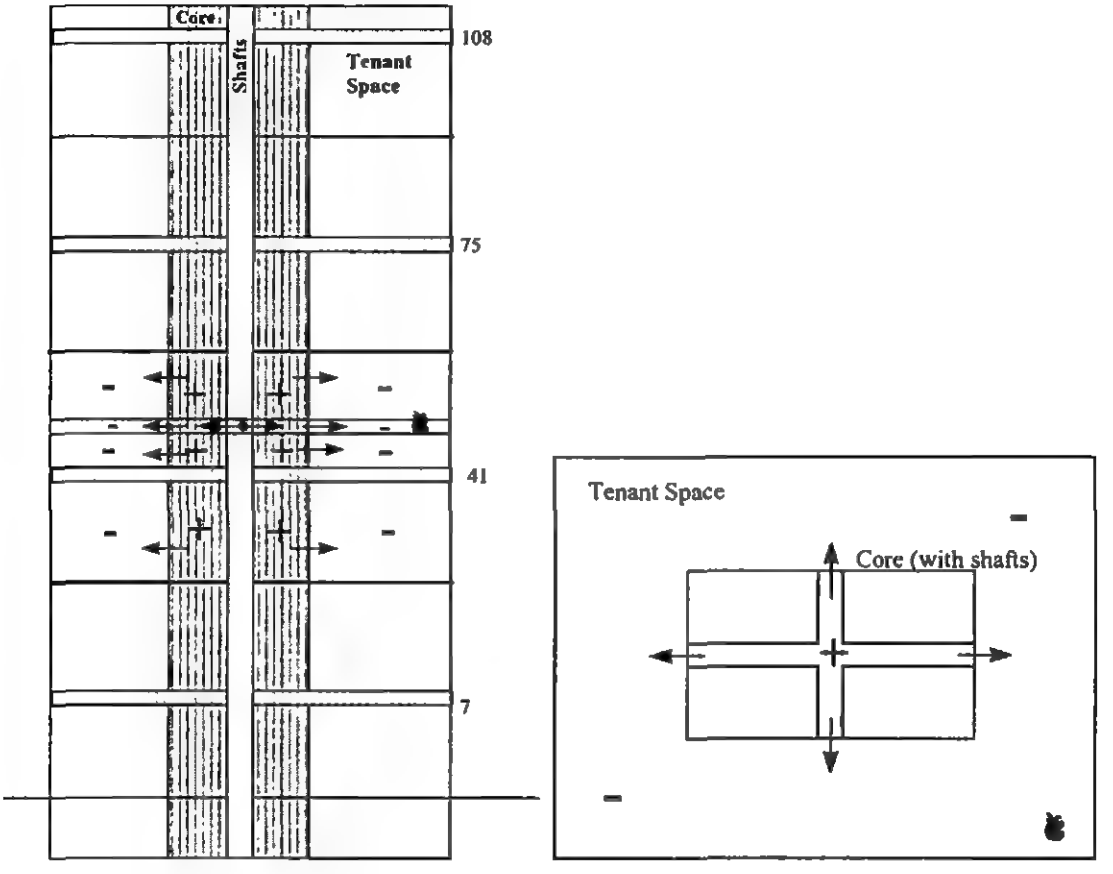
4.0 Smoke Control Modes

The study considered several conceptual smoke control designs, as well as simulations where no attempt at smoke control was made. Smoke control options were principally chosen from the currently available HVAC control selections, although simulations were made using concepts that would require modification to the existing HVAC systems.

For the purposes of this study, an HVAC zone in the towers is defined as those floors which are served by a given set of supply air fans, including peripheral air supply, inside space supply, and core supply.

One existing method of smoke management in the tower buildings is commonly called "Core Pressurization." For the purposes of this study, the term "Core Pressurization" is defined as the condition where the core supply fans are on, the toilet exhaust fans are off, the peripheral and inside space supply fans are off, and the inside space return fans are on and set to full exhaust. (See Figure 6)

Figure 6. Core Pressurization Smoke Control Mode



Elevation View **Plan View of Fire Floor**

5.0 CONTAM 96 Network Model

The network model CONTAM 96 (Walton, 1996) was used to analyze the movement of smoke in the complex.

Appendix B catalogs the physical dimensions, the geographical relationship of the spaces, the openings and other flow paths, the HVAC and smoke exhaust capacities and other data used in the CONTAM 96 modeling of the World Trade Center Complex and Towers.

The CONTAM 96 model is a interactive network model designed for analyzing the air movement and air quality in multi-zone buildings. The equations are derived from Bernoulli's equation for air flow and conservation equations for the spread of contaminants. The equations as reported by Walton are included in Appendix A. In addition, Appendix A provides information on the procedures used to validate the model.

An attempt was made to build a single model of the entire World Trade Center complex within CONTAM 96. The large size and complexity of the complex exceeded the capacity of the CONTAM 96 model within the constraints of this study. Two separate models were constructed: The first was a model of one of the towers, and the second was a simplified model of the complex, wherein the effects of the towers, the PATH terminal, the subway entrances, the Customs House, and the Hotel were estimated as in the previous study. (Hughes, 1996) The tower model included more than 3,200 zones and 14,000 flow elements, and the complex model had more than 470 zones and 1,470 flow paths.

To build the models, the complex was divided into zones comprised of spaces, rooms, atria, and other describable features. Appendix B contains diagrammatic sketches produced by CONTAM 96 detailing the arrangement of the WTC complex as used in this study.

Airflow sources (fans or entire HVAC systems) were modeled as simple air handling systems. A system is defined, and supply and return points are added to the appropriate zones according to the fan schedules developed, and described in Appendix B.

The contaminant produced by the fire was simulated as a mass in the zone of fire origin. The contaminant source term was entered as a time dependent variable following the data for mass loss rates derived from the heat release rate curves shown in Figures 1 through 5. The model cannot locate the fire to any specific point in the zone and, therefore, it is assumed that the mass produced by the fire is well mixed within that zone. This assumption is reasonable, though the model cannot consider a case of a fire located directly in front of an opening between two zones; for example, the escalator openings into 5 WTC.

Test measurements were taken during a visit to the site on June 28 - July 2, 1996. These were used to calibrate the initial conditions represented by the building as it stands at this time. The field measurements, procedures used, and data collected were reported in an interim report to the Port Authority, which is included herein as Appendix C. The wind pressure impact on the these buildings was also included in the model. (See Appendix D)

Upon completion of the Tower model, a series of simulations were conducted to calibrate the model. The simulations, illustrated in Cases nel-1 through nel-5 in Appendix E, were designed to replicate the physical conditions observed and measured during the site survey.

As anticipated, the simulations showed some disagreement between the simulation results and the measurements taken during the site survey. The principal difference was in the stair and elevator shaft pressures. Some difference was expected since the model was based on all doors being closed, and during the testing, an uncertain number of doors were open.

In order to fine tune the model, the leakage path areas for stair doors, passenger elevators, and selected other doors were increased. This distributed the leakage from the open doors throughout the full height of each shaft, a desirable approximation since it is reasonable to expect under the current building management systems that some doors will always be open, and that it is impossible to predict which doors these will be. The corrected leakage path areas are shown in Table B-2. Following these adjustments, the simulations gave results that are in reasonable agreement with the measurements obtained during the testing.

CONTAM 96 produces a massive amount of detailed data that can be difficult to present in a useful manner. To overcome this, the post processing procedure developed during the earlier

study was adapted further, and used to evaluate the life safety factors in each of the subdivisions (CONTAM 96 zones) in the model. Using the vision distance and COHb equations, the data were converted to estimates of the vision distance, CO concentration, and carboxyhemoglobin concentrations expected due to exposure to the fire produced environment.

For analysis purposes these results were sorted to report all zones where the vision distance was less than 200 ft. The data were then mapped on floor plan sketches of the Concourse, Plaza and Mezzanine. The shaded areas in the sketches show those zones where the vision distance was less than 200 ft. Appendix E shows the output data produced and selected sketches that are referenced in this report.

More than 200 different cases were evaluated during the study. Each was designed to evaluate the effects of changes to selected variables on the spread of smoke within the areas modeled. Several general groupings of cases were conducted, and are reported as:

1. Model calibration cases,
2. Tower studies: Total Floor burn-out cases,
3. Tower studies: Work Station fire cases,
4. Tower studies: Pressurization cases,
5. Tower studies: Tracer fire cases,
6. Tower studies: Fire detection system interaction cases,
7. Tower studies: Truck fire at loading dock cases,
8. Tower studies: Automobile fire in garage cases,
9. Complex studies,
10. Stairwell pressurization studies: Tower,
11. Stairwell pressurization studies: 4 & 5 WTC,
12. Elevator vestibule pressurization studies, and
13. PATH terminal fire studies.

Two important variables, weather and stair doors, were also considered during the simulations.

The impact of two extreme weather conditions on the performance of the smoke control system was evaluated. The extreme winter condition (to maximize the impact of the stack effect) was

simulated as 15°F outside temperature with a wind varying from 10 mph at street level to 60 mph blowing across the top of the towers. Using the wind pressure profile described in Appendix D, the pressure created by this wind at each level and each face of the building was modeled. The extreme summer condition (to maximize the impact of the reverse stack effect) was simulated as 90°F outside temperature with no wind blowing.

The impact of open and/or closed stair doors on the movement of smoke and the force required to open other closed doors in the stairwell was evaluated. In the Towers, the worst case for smoke control was modeled as all stair doors opened, except those stair doors on the fire floor, to simulate the effect of a simultaneous total egress from the building. Similarly, the worst case for door opening force was modeled as all stair doors closed, to simulate the impact of the smoke control system being placed in operation before egress begins. In 4 WTC and 5 WTC, the worst case for smoke control was also modeled as stair doors open, simulating egress of the fire door and the adjacent floor, and door opening force was based on all doors closed at the initiation of smoke control.

6.0 Studies Based on Smoke Control Cases

The separate cases were evaluated using CONTAM 96 models of the buildings and complex. Results of selected individual case studies are shown Appendix E. The cases were run to simulate the various potential fire exposure conditions and methodologies for smoke management. Discussion of the approaches and results are grouped by potential fire problem area below.

6.1 Fire Involving an Office Work Station in Sprinkler Protected Space.

It is the plan of the Port Authority to protect the entire World Trade Center Complex with automatic sprinkler protection. At present approximately 80 to 90 percent of the spaces in the office buildings are so protected. In accordance with the instructions of the Port Authority, all of the cases in this analysis are based on total sprinkler protection.

As discussed in Section 3.3.1, the rate of heat release curve developed by the National Research Council - Canada (Lougheed 1996) as shown in Figure 1 was used to represent the maximum rate of heat release and mass loss to be expected under office type sprinkler protection. This type of fire represents the worst case for the vast majority of the potential incidents in office space.

Cases LAM-9, LAM-10, NEL-7, NEL-12, NEL-41, NELS-63, NELS-63A, NELS-66, NELS-67, NELS-68, NELS-70, and NELS-71 all used the fire curve from Figure 1 as the source for heat and contaminant production. In each case the contaminant was located in the general office space. In every case smoke contamination was confined to the zone of fire origin or immediately adjacent zones and no life threatening conditions occurred beyond these zones. This limited spread of contamination occurred whether or not any smoke control measures were simulated. These cases demonstrate the ability of the Core Pressurization mode to confine the smoke from a small fire to the zone of origin.

As long as the sprinkler protection is present and in service and no extraordinary fire that overwhelms the sprinkler protection occurs (See Section 6.4 for discussion of such cases), the models show that there will be no smoke migration into exit routes or remote areas and no development of harmful conditions away from the immediate area of fire involvement.

6.2 Fire in Lobby of One or Two World Trade Center.

The lobby area in each of the towers has an air supply of approximately 180,000 cfm with the supply entering the lobby at or below the 2nd Floor slab. Approximately 170,000 cfm exhaust is provided with exhaust intakes near the top of the 6 story lobby. If these supplies and exhausts are kept operational at the time of fire and the exhaust is discharged without recirculation, smoke management for a fire within this atrium space can be achieved.

This analysis is based on the assumption that all areas under balconies will be sprinkler protected, in which case the conditions described in Section 6.1 apply for any fires initiating in the space under a balcony.

The case of concern here is a fire occurring under the open space between the Plaza Level balcony and the building core or on the Plaza Level balcony. The ability to maintain the smoke

level interface at a given position is described in NFPA 92B (NFPA, 1995) and expressed in terms of volume flow in the 1993 BOCA National Building Code. The BOCA form of the equation was used. It is expressed as:

$$V = 20.8 Q_c^{1/3} z^{5/3} + 3.98 Q_c \qquad \text{Equation 3}$$

where

V = volumetric rate of smoke inflow (rate of exhaust required) (cfm),

Q_c = convective fraction of the rate of heat release (Btu/s), and

z = height above the base of the source fire (ft).

In the above equation:

$$Q_c = f_c Q \qquad \text{Equation 4}$$

where

Q = total rate of heat release (Btu/s) and

f_c = convective fraction (taken as 0.7 in this report.)

The worst case fire in terms of the ability of the exhaust system is one with its base at the lobby (Concourse) floor level. Since the Plaza level (mezzanine) is not only open to the public but is also the level of exit discharge for two of the stairwells, it is important to keep smoke from a fire in the lobby high enough above the walking surface of the Plaza level to allow egress. The Plaza level slab is approximately 23 ft above the lobby slab. It is desirable to maintain the bottom of the smoke level from a fire at the lobby floor at least 7 to 10 ft above the Plaza level slab.

Using the exhaust flow rate of 170,000 cfm, and solving Equations 3 and 4 for the height above the Lobby slab (z) and total fire size (Q) indicates that the existing system can maintain the smoke layer from a fire of approximately 11,000 Btu/s at a level 33 ft above the Lobby slab (10 ft above the Plaza level slab). The equations also indicate that the smoke layer will be maintained 7 ft above the Plaza level slab even if the fire should be able to sustain a rate of heat release of 15,000 Btu/s. Any fires initiating on the Plaza level would have a lesser impact on smoke layer level for the same fire.

In the NIST Kiosk test (Mitler, 1996) the maximum rate of heat release experienced when the kiosk was allowed to burn itself out without sprinkler or other suppression action was 3000 Btu/s.

Even in that case the peak 3000 Btu/s was sustained for only a brief period of time. Nelson and Forssell (1994) report the heat release rate of wood (pine) as between 12 and 24 Btu/s-ft^2 depending on the energy feed back from the exposing flame. The production of 11,000 Btu/s from wood or similar common cellulosic based materials (as might be used in a booth or display) would require the involvement of about 500 to 1,000 ft^2 of burning surface. For gasoline the rate of heat release is approximately 200 Btu/s-ft^2 (Babrauskas, 1995). A gasoline pool of approximately 55 ft^2 (8 ft diameter) with sufficient fuel depth to sustain that level of burning would also produce a sustained fire of 11,000 Btu/s. Both of these examples are expected to exceed any exposure fire likely to occur in the lobby.

The only openings from elevator shafts into the lobby are at the 1st Floor level. During business hours and during other than severe winter conditions, the stack effect impact in the lobby are modest and it is reasonable to expect that little if any of a rising plume from a fire might be diverted from the upper portions of the lobby into the elevator shafts. During severe winter cold, when the fans are at reduced settings, a strong inflow of air from either the exterior of the building or the Concourse into the lobby can be present. In such a case this inflow can divert the rising fire plume into the elevator shafts and transport at least a portion of the smoke to remote areas of the building. In the case of such a fire it is important to boost the pressure in the shafts to counter this in flow without shutting down lobby exhaust.

6.3 Truck Fire at the B-1 Level Loading Dock.

The principle loading dock for the complex is located at the B-1 Level adjacent to 1 WTC and 2 WTC. Delivery vehicles of all sizes use this facility. Some of the vehicles are full size, over the road tractor-trailer combinations. As discussed in Section 3.3.4, evaluations were made of the impact of a fire within the cargo of such a large vehicle. The fire case is based on an incident involving a truck parked at the dock with its cargo doors open and a flashed-over fire within the trailer. As noted in Section 3.3.4, a fire of approximately 14,000 kW with high carbon monoxide production is possible and is used as the basis for the simulation. See cases NEL-8, NEL-9, NEL-14, NEL-15, NEL-16, NEL-19, NEL-27, NEL-28 and NEL-29.

The separation between the loading dock and the B-1 levels in each of the towers consists of two "air lock" doors and two rolling steel doors. The "air lock" doors are composed of a vestibule

with a power operated sliding door at one end and a heavy rubber door at the other end. At the time of the visit to the site by the project team, one of the "air lock" doors in 2 WTC was defective in that the power door was open and inoperable, and the rubber door had a large gap between the door and its frame. The analysis in this report are based on the necessary repairs being made to these doors. The rolling steel doors open directly from the B-1 level to the loading dock. At the time of the site visit in August, 1996, one of these doors was open in each building. The various cases are based on the "air lock" doors always being in the closed position. Some cases address the situation with the rolling steel doors open, others with these doors closed.

Cases NEL-8 and NEL-9 simulate the conditions on a severe winter day with building systems in normal operation and no special smoke management efforts. Case NEL-8 simulates smoke spread with the rolling steel doors closed. Case NEL-9 simulates the situation with these doors open.

With no smoke control and the rolling doors closed, Case NEL-8, smoke migrates in the general area of Level B-1 at an approximately linear rate, reaching an obscuration level of 50 ft in 30 minutes. Smoke also spreads into Stair 3 but not into the basement stair, and into the several elevator shafts that serve the B-1 level. Vision distance in Stair 3 at the B-1 level drops at a linear rate over 30 minutes to a vision distance of approximately 100 ft. Smoke in Stair 3 also migrates at a lesser density to Level B-2 and B-3 of that stair. The area of the loading dock has severe decreases in vision distance, but the loading dock ventilation system prevents significant smoke migration to the rest of the garage area.

With no smoke control and the rolling doors open, Case NEL-9, smoke migrates into both stairs, and through the elevators at a rate approximately four times that as with the doors closed. The same applies to the general space in the B-1 level where the vision distance drops to about 12 ft in 30 minutes. Smoke spreads up through the elevator shafts to the core spaces in the building on all floors above the 9th, migrating to all three stairs.

A number of additional cases were simulated with different arrangements of the building fans to attempt to stop or restrict smoke migration. In no case was it possible to completely prevent any smoke from entering the towers under severe winter stack effect conditions. The best results were produced in Case NEL-15 where all of the return, exhaust and transfer fans serving the sub-

grade areas of the towers and the lobby return fans were shut off. In this case the rolling doors are closed. Significant smoke intrusion is limited to the B-1 level. The maximum smoke density occurs 20 minutes into the fire. At 20 minutes, vision distance in the general B-1 area is reduced to about 75 ft. and some light smoke has entered the elevator shafts serving this floor but is diluted and significantly reduced in density as it reaches other levels. In less severe conditions (Case NEL-16) this arrangement of fans keeps Level B-1 clear of smoke. Under summer conditions this fan arrangement can exclude smoke even if the rolling steel doors are open.

A number of other cases (NEL-19, NEL-28 and NEL-29) were run to assess the possibility of managing smoke from a truck fire during severe winter conditions with the rolling doors open. No successful arrangements were found. In all cases where the rolling doors were open under conditions of winter stack effect (i.e., modeled as 15°F and wind conditions ranging from about 10 mph at the base of the complex to 60 mph across the roof of the towers) the smoke could not be held back but extended through significant portions of the affected building.

6.4 Impact of an Uncontrolled Fire

6.4.1 Fire in 1 WTC or 2 WTC

On rare occasions there have been uncontrolled fires of major consequences in modern office buildings. Examples include the May 1988 fire in the 60 story First Interstate Bank Building in Los Angles (Nelson, 1989) and the February 1991 fire in the 38-story, One Meridian Plaza Building in Philadelphia (Klem, 1991). Neither of these buildings was sprinkler protected at the time of the fire. To date there is no record of such an uncontrolled fire in a sprinkler protected building. In both the Los Angles and Philadelphia fires, the initial source fire would have been controlled by sprinklers.

For such a fire to occur in a WTC Complex office building once sprinkler protection is provided, it would require either that the sprinkler system was turned off or otherwise seriously impaired, or that a fire initiated in a fuel arrangement that produced a fire beyond the control capabilities of the sprinkler protection provided. Such a fire would also have to exceed the capabilities of the New York City Fire Department. The sprinkler system being installed in the WTC office areas is

designed for office type occupancies. It is pertinent to note that in both the Los Angles and Philadelphia fires the fire department was seriously hampered by faults in the building standpipe and water supply system that seriously depreciated their ability to apply water from hose stream to the fire. It is understood that the standpipe systems in the WTC complex are regularly tested and in good order.

Testing of mobile shelving units at the National Research Counsel of Canada (Lougheed, 1994) demonstrated that mobile shelving unit of types currently promoted for office use can overtax sprinkler systems of the design being provided in the WTC office buildings. None of these storage units were observed during the site survey, but it is understood that the Port Authority does not have control over tenant installations of such devices. To the extent that the management of these buildings can prevent sprinkler interruption, and either prevent or provide special fire protection for mobile shelving or other unexpected fuel concentrations, the threat of an uncontrolled fire is not felt to be credible. The following analysis is designed to present the capabilities and limitations of various smoke control approaches if such a fire were to occur.

In both the Los Angles and Philadelphia fires, the fire initiated on one side of the building and progressed, breaking windows as it moved around the building until all of the windows on the affected floor were broken out. In each of these cases approximately an hour was involved in this phase of burning. While there is no certainty that an uncontrolled fire in the WTC would progress in the same manner, this is the best model available and has been used as the base condition in this analysis. The rate of heat release assumed is as shown in Figure 2.

Cases NEL-10, NEL-11, LAM-12A2 and LAM-13 demonstrate that under severe winter conditions without smoke control, an uncontrolled fire of the type modeled (i.e., having a rate of heat release as plotted in Figure 2) could readily spread heavy smoke and lethal concentrations of carbon monoxide through the entire building above the lobby. Full fire buildup is predicted to require about 3 hours. Intolerable conditions would occur on the floors close to the fire and in the stairwell much earlier in the fire. The exact timing depends on the position of the doors between the fire source and the building core, and the extent of smoke passage through ceiling voids into the core area.

Case LAM-12C demonstrates that core pressurization alone will be incapable of managing the smoke from an uncontrolled fire with window breakage and a moderated wind impact on the broken windows.

Cases LAM-24, LAM-25, LAM-27, LAM-28, and LAM-29 illustrate another phenomenon that occurs when shutting off the supply fans to the fire floor. Smoke enters the supply ducts and spreads to other floors in that HVAC zone, and from them into the elevator and stair shafts in some cases. The fire dampers on the ducts will not operate in time to prevent the spread of significant levels of smoke. In order to prevent this spread of smoke, it is necessary to pressurize the supply ducts to the fire floor (i.e., leave the supply fans running during the fire).
The often held view that leaving the supply fans operating during a fire would "fan" the fire does not apply to these buildings. The natural speed of air intake to the base of a fire plume is about 200 ft/min. Any air entering the fire plume at a lower velocity will not increase the natural burning rate of the fire. The flows that would occur in the towers due to the use of the supply fans to pressurize the ducts would not produce velocities in excess of 200 fpm at the base of a fire. Further, the large fire postulated in these cases cannot occur unless the windows break out. Once broken, the open windows would create a much more energetic flow than the HVAC system. Hence, there is no harm encountered from continuing the HVAC supply to the fire floor during a major fire. Rather, there is a clear benefit to leaving the supply fans operating to prevent the spread of smoke through the ducts and encourage more complete combustion, with resultant reduction in the generation of the toxic carbon monoxide. However, there can be, in the case of an uncontrolled fire, an increase of the flow of fire products, including flame, out the broken windows.

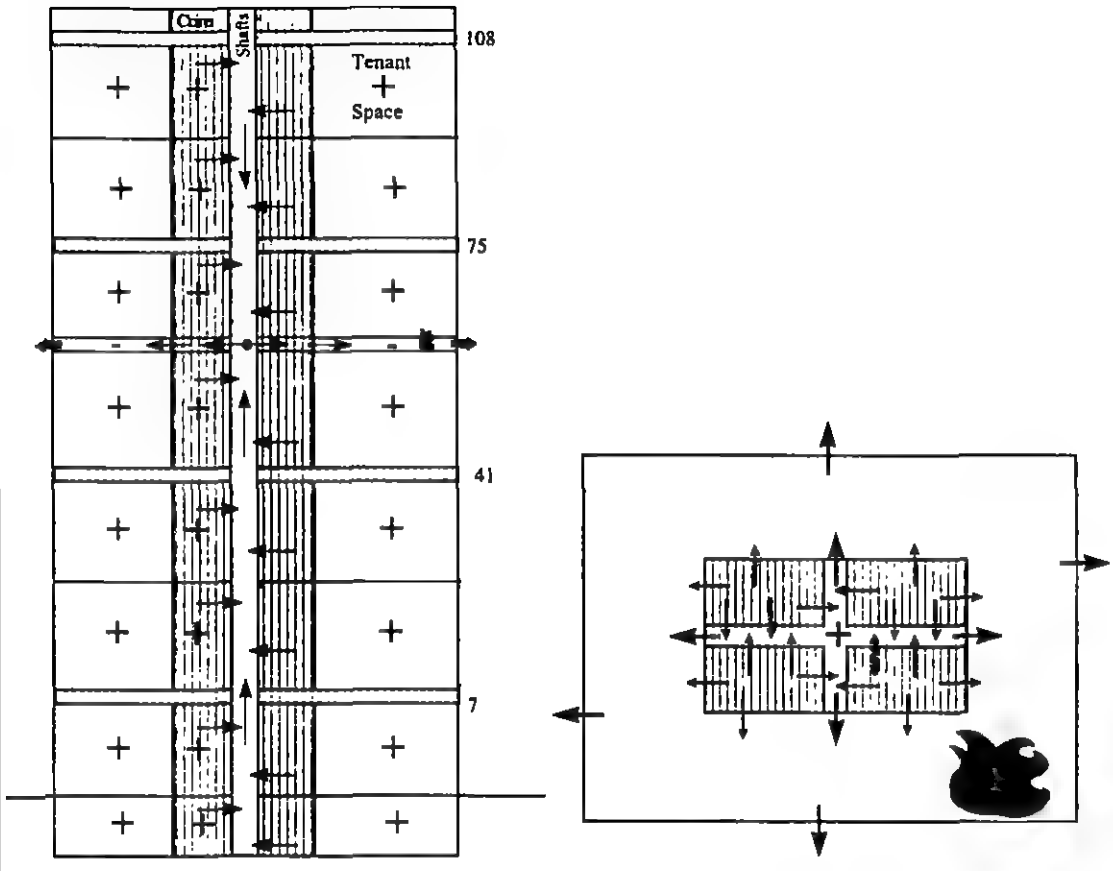
A large number of cases were run to test the feasibility of using the various arrangements of the HVAC system to confine smoke to the floor of origin and keep the stairs clear of smoke should an uncontrolled fire occur in one of the towers. A number of approaches that could provide the protection were discovered. The most suitable and simplest approaches are demonstrated in cases LAM-29, LAM-29S, LAM-87, LAM-87S, LAM-88, LAM-88S, LAM-89, LAM-89S, LAM-89A, and LAM-89AS. These cases show the effectiveness of "Positive Pressure Ventilation" in controlling the spread of smoke from a major fire. Positive Pressure Ventilation (See Figure 7) is accomplished by the following:

1. The supplies for the interior spaces and peripheral systems for all of the systems in the building are kept on,
2. The returns from the interior spaces for the HVAC zone that includes the floor of fire involvement are set to exhaust and also kept operating,
3. All the toilet exhausts for the entire building are shut down, and
4. The returns on all other floors are shut down.

Some of the cases were based on assuming that all of the floors served by a single MER constituted a zone. The MER's at 41st and 75th floors serve floors above and below the MER floor. The supply fans in these MER's serve either above the MER floor or below it but not in both directions. The return fans, however, use a common plenum in the MER and each fan actually pulls air from both above and below the MER. A number of the cases run were based on HVAC zones covering the full extent of the floors served by these two MER's, others were run assuming that a means is installed to separate the return into two systems, one for the floors served above the MER, the other for the floors served below the MER. For these cases it was then assumed that the HVAC zone consisted of only the floors served by the MER and on the same side of it as the fire. Both approaches worked to the same order of effectiveness.

These and all of the other workable cases, however, have the same limitations. First they will not work properly until the fire floor has a vent. The expected vent is one or more windows broken out by the fire. Secondly, under certain conditions, such a situation where the first windows to break out are on the downwind (lee) side, a wind of more than approximately 15 mph at the level of the fire can result in pressure differentials sufficient to prevent their use by persons evacuating the fire floor. This problem occurs only on the fire (vented) floor. For this reason this approach should never be initiated until the floor of fire involvement is totally evacuated.

Figure 7. Positive Pressure Ventilation



This smoke control approach is essentially a positive ventilation approach that builds up a positive pressure in the building, in some of the cases as high as 3.0" w.g. between the building and the exterior. The venting of the fire floor when the windows are broken out moves the pressure boundary back into the building to the next line of partitions, the core or corridor walls. If these partitions should fail as the fire progresses or doors are standing open in the partitions,

the pressure boundary then moves to the next boundary, normally the stairwells and other shafts. Resulting pressures on the fire floor and at the lobby doors are shown in Tables 6.3, 6.4, and 6.5.

In this case the amount of air passing thorough the fire floor will be significant, in some cases greater than 100,000 cfm. It will vent through the broken windows and may push some of the fire gases out those windows as flame and smoke. Since all of the ducts and shafts will be pressurized, the products will not be pushed to other locations in the building.

6.4.2 Fire in 4 WTC or 5 WTC

From a smoke management aspect, 4 WTC and 5 WTC are significantly different from the towers. Four WTC is well separated from the Concourse and all vertical openings in the building are reasonably enclosed. Five WTC, however, has escalator opening from the Concourse Level to the 5th Floor and wide openings between the discharge level of the escalator and the Concourse. For this reason 5 WTC functions partially as an extension of the Concourse while 4 WTC functions more nearly independent of the Concourse.

The fan systems for the major portions of both 4 WTC and 5 WTC are located in MER's on the top floors of these buildings. For this reason it is not possible to consider approaches involving zoning of entire fan systems as evaluated for the tower buildings.

Case NELA-51 simulates an uncontrolled fire on the 4th Floor of 5 WTC without any smoke control actions. The simulation shows major movement of smoke and gases throughout 5 WTC and migrating through the Concourse and into 1 WTC, 2 WTC and 4 WTC. There is no migration into basement areas. There is no indication of migration into the PATH Terminal. In other cases with the windows on the windward side of the building broken out by the fire (Cases NELA-51A, NELA-51B, NELA-51C, NELA-51G and NELA-51I) the smoke is forced into the Concourse, the PATH terminal and the other office buildings.

Case NELA-51D demonstrates that smoke migration can be held to 5 WTC and the portion of the Concourse immediately adjacent to the Concourse entrance to 5 WTC by enclosing the escalators.

Case NELA-51M demonstrates that smoke migration can be held to 5 WTC by providing a partition composed of doors that will close upon detection of smoke in 5 WTC and by pressurizing the stairs and freight elevator vestibules in 5 WTC as described in Sections 6.5.2 and 6.8.

Cases NELA-51J and NELA-51K demonstrate that smoke from an uncontrolled fire with windows broken on the windward side under severe winter conditions can be confined to 5 WTC by air flow only if all of the Concourse systems are turned to supply and sufficient adjustments are made in the tower building to place the tower building lobbies in a positive pressure condition relative to the Concourse.

Case NELA-57 simulates an uncontrolled fire on the 8th Floor of 4 WTC. Smoke migration extends through out 4 WTC and into the south east quadrant of the Concourse, with very heavy smoke at the elevator lobbies for the 4 WTC elevators.

Case NELS-65A simulates a fire involving a sprinkler protected work station on the 4th Floor of 5 WTC. No smoke control is modeled. Under these conditions the migration of smoke is confined to modest levels on the occupied space of the 4th Floor. This demonstrates that smoke migration from a sprinkler protected work station will not extend beyond the immediate area of origin even without smoke control efforts.

Case NELA-60 similarly simulates a fire involving a sprinkler protected work station on the 8th Floor of 4 WTC. As in the other building, the indicated spread of smoke was limited to tolerable concentrations on the 8th Floor with no migration into stairs or elevators.

A number of cases were simulated in an attempt to develop a means of confining smoke to the floor of origin without over pressuring the stairwells. No successful approaches were found.

6.5 Fire in Core

The impact of a fire in the Core area was assessed by placing the Workstation fire discussed in Section 3.3.1 in either the corridors in the Core area or in the service elevator vestibule. The typical fire that is anticipated in the Core area would be a trash bin fire under the sprinklers, in which event, a maximum rate of heat release would be on the order of 400 kW, with little of the

fire shielded from the operating sprinklers. The 1 MW workstation fire with significant shielding represents a much greater than expected exposure.

Cases LAM-90, LAM-91, LAM-91S, LAM-92, LAM-92S, LAM-93, LAM-93S, LAM-94, LAM-94S, LAM-95, and LAM-95S demonstrate the effects of such a fire. The model shows that with no smoke control systems activated, and all HVAC systems operating normally, a fire in the corridor results in smoke spread throughout the floor of origin and up the elevator shafts. When the Core Pressurization smoke control mode is set, the smoke is confined to the Core and Tenant areas on the floor of fire origin. In all cases the predicted COHb levels are well within the tenability limits established for this study, i.e., less than 12%.

With the fire in the service elevator vestibule, and the Core Pressurization mode set, smoke is confined to the vestibule, the Core, the Tenant space, and in some cases the elevator shaft serving the vestibule, depending on the flow through the elevator door. In these cases, predicted COHb levels in the vestibule exceed the tenability criteria established, but do not spread beyond the small elevator vestibule.

6.6 Stairwell Pressurization

6.6.1 Stairwells in 1 WTC and 2 WTC

Each of the towers has three main stairs. Stairs 1 and 2 start at the 2nd floor level and continue to the roof with interruptions at the 42nd, 48th, 76th and 82nd Floors. Stair 3 starts at the B-6 level and continues to the 108th Floor with an internal stairwell door at the 1st Floor separating the portions of the stairwell below grade from that above grade. This stair is also interrupted at 76th Floor.

Stair pressurization in tall buildings presents special problems as a result of the stack effect and the impact of other shafts, primarily elevators, on the ability to pressurize a stairwell. Klote and Milke (1992) propose the following equation to estimate the height limit for stairwell pressurization.

$$H_m = K_m \frac{\Delta P_{max} - \Delta P_{min}}{\frac{1}{T_O} - \frac{1}{T_B}} \left(1 - \left(\frac{A_{SB}}{A_{BO}}\right)^2\right) \qquad \text{Equation 5}$$

where

H_m = height limit (ft),

ΔP_{max} = maximum allowable pressure difference between the stairwell and the building ("w.g.),

ΔP_{min} = minimum allowable pressure difference between the stairwell and the building ("w.g.),

T_O = outside design temperature (°R),

T_B = building temperature (°R),

A_{SB} = flow area between the stairwell and the building (ft^2),

A_{BO} = flow area between the building and the outside (ft^2), and

K_m = coefficient (0.131)

A calculation of the approximate height limit was made using Equation 5. The calculation was based on an outside temperature of 15°F, an inside building temperature of 70°F, a maximum acceptable pressure of 0.35" w.g., a minimum acceptable pressure of 0.05" w.g., a flow area between the stairwell and the building of 1 ft^2 per floor per stairwell and a flow area between the building and the outside of 2 ft^2 per floor. Equation 5 indicates a height limit of 224 ft or approximately 20 floors. Any change in criteria to reduce the design temperature difference or revise the pressure limitations will change the calculated height limit. Equation 5 does not consider the impact of the elevator shafts or wind forces on the building, both of which can increase the tendency of the stairwell system to exceed pressure limitations. The equation does, however, provide explanation for the difficulty experienced in prior attempts by the Port Authority to develop stairwell smoke control for the stairwells in the towers.

As previously discussed, stair pressurization is not feasible in 1 WTC and 2 WTC. However, core pressurization will keep smoke out of the exit passageways for all expected fires once sprinklers are installed. In the unlikely event of an uncontrolled fire, the building fans can be used to place the building in the positive pressure ventilation mode to keep the stairs and

elevators smoke clear. (See Section 6.4.1.) No other successful approach to stair pressurization was found.

6.6.2 Stairwells in 4 WTC and 5 WTC

All of the stairs in 4 WTC and 5 WTC are shorter than the height limit developed using Equation 5. Each of the stairs in these buildings except the north Stair in 4 WTC consists of interlocking (or scissors) stairs that are not aerodynamically separated.

An initial rate of air injection of 800 cfm per floor per stair (1600 cfm for the interlocking stairs) was tested using the CONTAM model. (See Figure 8.) Cases NELS-63D and NELS-63E cover the results for an exterior temperature of 15°F with wind conditions that produce an air speed of approximately 15 mph across the roof of this building. The 800 cfm per floor per stair flow rate worked well for the stairs in 4 WTC. Table 6.1 shows the results for each Stair with all doors closed except those on the 8th and 9th floors and at the exit level. This determined the lowest air flow which indicates a positive pressure with the doors open. It also indicates a range of pressures of 0.11 to 0.24" w.g. with all of the doors closed.

In 5 WTC, however, pressurization of the stairwell will not be as simple. In this building the flow needed to produce a positive flow on all floors was approximately 1,750 cfm per floor per stair (3,500 cfm per floor for interlocking stairs.) This resulted in significant over pressures (in some cases exceeding 1" w.g.) with the doors closed. Cases NELS-63A and NELS-63B form the basis for the results shown in Table 6.2. It is believed that the escalator openings and the openings from 5 WTC into the Concourse cause this need for a high flow when doors are opened. It is, however, possible to successfully pressurize these stairs if a barometric relief or other means of relieving the over pressure when all the doors are closed can be provided.

Figure 8. Stair Pressurization Concept

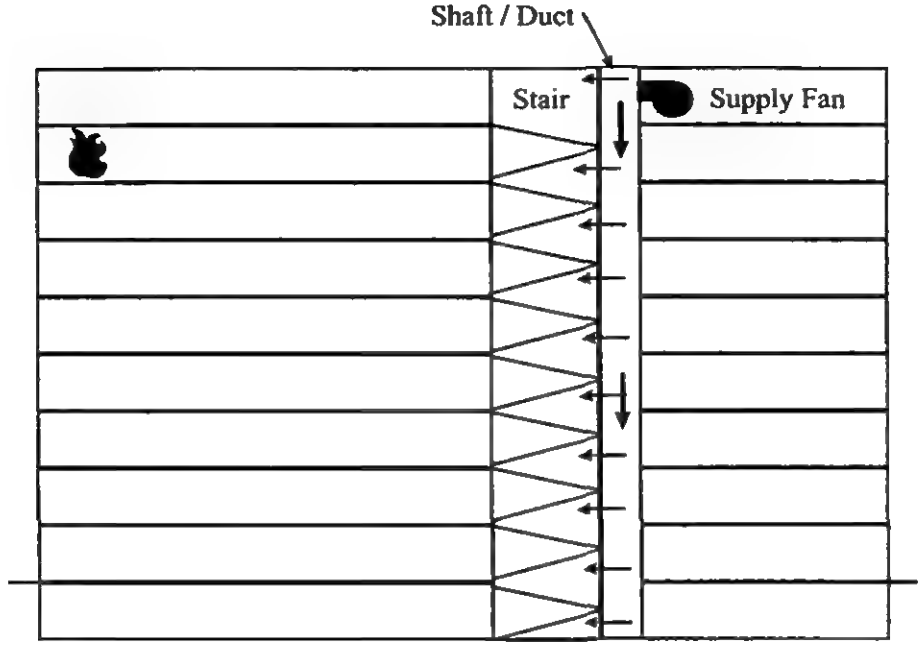


Table 6.1. 4 WTC Stair Pressurization Summary

Floor	Center Stair		West Stair		North Stair	
	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)
9	0.23	0.004*	0.12	0.004*	0.13	0.005*
8	0.23	0.005*	0,14	0.005*	0.13	0.005*
7	0.22	0.007	0.11	0.007	0.11	0.005*
6	0.22	0.008	0.11	0.008	0.11	0.006
5	0.22	0.008	O.11	0.008	0.11	0.006
4	0.22	0.008	0.11	0.008	0.11	0.007
M	0.22	0.01	0.11	0.01	0.11	0.007
P	0.21	0.001*	0.11	0.001*	0.11	0.005
C	0.24	0.009			0.14	0.007*
B-1						
B-2	0.22	0.007			0.11	0.007

- = OPEN DOORS

Table 6.2. 5 WTC Stair Pressurization Summary

Floor	West Stairs		Center Stairs		South Stairs	
	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)
9	0.28	0.042*	1.13	0.037*	0.84	0.031*
8	0.19	0.025*	1.12	0.006*	0.87	0.004*
7	0.19	0.001	1.05	0.041	0.76	0.043
6	0.18	0.061	1.05	0.04	0.75	0.043
5	0182	0.033	1.04	0.012	0.75	0.016
4	0.17	0.027	1.04	0.005	0.75	0.011
M	0.19	0.039	1.07	0.019	0.78	0.025
P	0.31	0.013*	1.19	0.107	0.70	0.12*
C			1.22	0.129*		0.007*

* = OPEN DOORS

6.6.3 32 Floor HVAC Return Zone vs. 16 Floor HVAC Return Zone

Numerous cases were run to evaluate the effect of zoning of the HVAC system into 16 floor zones rather than 32 floor zones (typical), at the MER.

Cases LAM-29, LAM-29S, LAM-87, LAM-87S, LAM-88, LAM-88S, LAM-89, LAM-89S, LAM-89A, and LAM-89AS illustrate the impact of various arrangements of HVAC return system zoning. As discussed in Section 6.4.1, all of these Cases exhibited similar smoke movement performance in the model. That is, in each Case the model predicts that the smoke will be confined to the floor of fire origin. Given that there will be some time between the start of the fire, the completion of egress from the fire floor, and the breaking out of an exterior window and the initiation of the positive pressure ventilation mode of smoke control, it is expected that some smoke will migrate to other areas of the building (principally through the un-pressurized supply

ducts) before the positive pressure mode is activated. The model indicates that this migration will end upon activation of the positive pressure mode.

Since the positive pressure mode of smoke control is expected to over-pressurize the stair doors on the fire floor, special attention was given to the pressures developed on the stair doors to see if varying the number of floors in a return zone could lower the pressure differences. Tables 6.3, 6.4, and 6.5 show the pressure differences predicted across the stair doors, and across exit doors from the building on the Concourse and Plaza levels, at various levels in the tower. While there are clear differences between the pressures predicted between the 16 floor return zone and the 32 floor return zone, there is not a definable trend, especially when considering the effects of exterior weather conditions and height of the fire in the building. (Winter conditions were simulated as an outside temperature of 15°F and a westerly wind of 60 mph across the top of the towers. Summer conditions were simulated at an outside temperature of 90°F and an easterly wind of 60 mph across the top of the towers. In all of these cases, the west windows were broken out by the fire.)

Table 6.3. Pressure Differences (in. w.g.) and Door Opening Force (in lb.)* Across DoorsDuring Positive Pressure Ventilation Smoke Control Mode for a Simulated Uncontrolled Fire on the 9th Floor

	16 Floor Return Zone (9-25)			
	Winter (LAM-87)		Summer (LAM-87S)	
	Time 0:00	Time 1:30	Time 0:00	Time 1:30
Stair 1	0.006". 10.4 lb.	1.20" 80.4 lb.	0.03" 11.8 lb.	2.46" 154.4 lb.
Stair 2	0.008" 10.5 lb.	1.20" 80.4 lb.	0.04" 12.3 lb.	2.46" 154.4 lb.
Stair 3	0.040" 12.3 lb.	1.20" 80.4 lb.	0.11" 10.6 lb.	2.62" 163.7 lb.
Handicap door on 1	1.50" 98.0 lb.		2.50" 156.7 lb.	
Handicap door on 2	1.70" 109.8 lb.		2.30" 145.0 lb.	
Plaza doors on 2	1.80" 115.6 lb.		2.70" 168.4 lb.	

* Door opening force is calculated as described in Section 6.7.

Table 6.4. Pressure Differences (in. w.g.) and Door Opening Force (in lb.)* Across Doors During During Positive Pressure Ventilation Smoke Control Mode for a Simulated Uncontrolled Fire on the 25th Floor.

	16 Floor Return Zone (25-40)				32 Floor Return Zone (25-58)			
	Winter (LAM-89A)		Summer (LAM-89AS)		Winter (LAM-89)		Summer (LAM-89S)	
	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30
Stair 1	0.053" 13.1 lb.	1.30" 86.3 lb.	0.013" 10.8 lb.	2.57" 160.8 lb.	0.013" 10.8 lb.	0.833" 58.9 lb.	0.004" 10.2 lb.	2.07" 131.5 lb.
Stair 2	0.058" 13.4 lb.	1.30" 86.3 lb.	0.028" 11.6 lb.	2.56" 160.2 lb.	0.010" 10.6 lb.	0.831" 58.8 lb.	0.012" 10.7 lb.	2.07" 131.5 lb.
Stair 3	0.009" 10.5 lb.	1.35" 89.2 lb.	0.064" 13.8 lb.	2.68" 167.3 lb.	0.027" 11.6 lb.	0.850" 59.9 lb.	0.050" 13.9 lb.	2.14" 135.6 lb.
Handicap door on 1	1.53" 99.8 lb.		2.54" 159.0 lb.		1.03" 70.4 lb.		2.04" 129.7 lb.	
Handicap door on 2	1.77" 113.9 lb.		2.30" 145.0 lb.		1.27" 84.5 lb.		1.80" 115.6 lb.	
Plaza doors on 2	1.8" 115.6 lb.		2.74" 170.8 lb.		1.30" 86.3 lb.		2.23" 140.9 lb.	

* Door opening force is calculated as described in Section 6.7.

It is possible to postulate a set of conditions where there is a benefit that can be derived from segregating the return air shafts into 16 floor zones. However, the smoke control settings that would result from such conditions would be exceedingly complex, and as such, less reliable. The recommended smoke control strategy for the rare, extreme, fire in a tower—Positive Pressure Ventilation—provides a simple and more reliable set of control settings, as well as effective management of the spread of smoke.

Table 6.5. Pressure Differences (in. w.g.) and Door Opening Force (in lb.)* Across Doors During Positive Pressure Ventilation Smoke Control Mode for a Simulated Uncontrolled Fire on the 86th Floor.

	16 Floor Return Zone (78-91)				32 Floor Return Zone (59-91)			
	Winter (LAM-29)		Summer (LAM-29S)		Winter (LAM-88)		Summer (LAM-88S)	
	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30
Stair 1	0.01" 10.6 lb.	1.18" 79.2 lb.	0.03" 11.8 lb.	0.28" 26.4lb.	0.004" 10.2 lb.	0.764" 54.8 lb.	0.038" 12.2 lb.	2.39" 150.2 lb.
Stair 2	0.01" 10.6 lb.	1.18" 79.2 lb.	0.01" 10.6 lb.	0.28" 26.4lb.	0.008" 10.5 lb.	0.760" 54.6 lb.	0.005" 10.3 lb.	2.36" 148.5 lb.
Stair 3	0.07" 14.1 lb.	1.24" 82.8 lb.	0.07" 14.4 lb.	0.29" 27.0 lb.	0.055" 13.2 lb.	0.838" 59.1 lb.	0.070" 14.1 lb.	2.43" 152.6 lb.
Handicap door on 1	1.62" 105.1 lb.		2.60" 162.6 lb.		1.08" 73.4 lb.		2.15" 152.6 lb.	
Handicap door on 2	1.87" 119.7 lb.		2.30" 145.0 lb.		1.32" 87.5lb.		1.91" 122.0 lb.	
Plaza doors on 2	1.9" 121.5 lb.		2.80" 174.3lb.		1.35" 89.2lb.		2.35" 147.9 lb.	

Door opening force is calculated as described in Section 6.7.

6.7 Open Tenant Stairwell

The presence of open stairs between floors within the tenant spaces was confirmed by both observation and by report. Two separate cases are of interest. The first in the case where the stair is entirely within an HVAC zone. (i.e., the floors at the top and the bottom of the open stair are in the same HVAC zone.) The second case is where the stair crosses the zone boundary.

6.7.1 Within a Zone

Numerous cases were run with an open tenant stair between the 35th and 36th floors. No discernible effect was observed. The principal avenue of smoke spread in all cases where it spread beyond one floor were the many shafts in the buildings.

6.7.2 Breaching Zone Boundaries

Cases LAM-9, LAM-10, LAM-21, LAM-22, and LAM-23 were simulated to evaluate the effect of an open tenant stair breaching the HVAC zones. In cases LAM-9 and LAM-10, workstation fires were simulated on the floor both at the top of the tenant stair, and again at the bottom of the stair. No smoke control was simulated for these cases since prior cases had demonstrated that sprinklers effectively control the production of smoke under the workstation fire simulations. Minor air flow up the stair was noted in the simulations, but insufficient quantities of smoke were transported to the adjoining floor to obstruct vision. Similarly, dangerous levels of CO did not occur on the adjoining floor.

Cases LAM-21, LAM-22, and LAM-23 also show the effect of an open tenant Stair breaching the HVAC zones. In these cases, a total floor burn out was simulated on the floors at the top and bottom of the tenant stair (floors 24 and 25), as well as spreading from the lower floor to the upper floor (LAM-23). The smoke control strategy modeled in these cases included core pressurization on floors 9-24, and full pressurization (all supply fans on and all return and exhaust fans off) on all other floors in the building. This arrangement pressurized floor 25, the floor at the top of the open stair, and produced a strong flow down the stair from 25 to 24. Severe winter weather and wind conditions were included. In each of these cases, the smoke did not spread through the open stair. Rather, the smoke spread up the un-pressurized supply air ducts from the fire floor to the inside spaces on floors 20 to 25. We conclude that the effect of the open stair on smoke movement is minimal due to the pressurization possible with the HVAC system.

6.8 *Pressurization of Elevators for Possible Use For Evacuation of Handicapped Persons.*

As with the stairs, there is no practical way to pressurize elevators in the Tower buildings by direct injection of fresh air into the elevator shafts. Also, while on some floors vestibules are provided for freight elevators, this is not true on all floors and there is no space to install vestibules where none now exist. For this reason the pressurization of vestibules is not a viable approach.

As previously discussed, core pressurization, in 1 WTC and 2 WTC will keep smoke out of core and elevators for all expected fires once sprinklers are installed. In the unlikely event of an uncontrolled fire, the building fans can be used to keep the stairs and elevators smoke clear. See Section 6.4.1.

In 4 WTC and 5 WTC the above approach is not feasible. In each of these buildings the freight elevators have vestibules on all floors from the Concourse level to the top (9th) floor level. Analysis was made of the potential of using air injection into these vestibules as the means of excluding smoke from these spaces so that they could by developed into areas of refuge where handicapped persons could take shelter or evacuated using the freight elevators.

An initial estimate of the flow rate required was made using the orifice flow equation form contained in Klote and Milke (1992). The specific form of the equation used is presented as Equation 4.8a in their book and is as follows.

$$Q = K_f A \Delta P^{1/2} \qquad \textbf{Equation 6}$$

where

Q = volumetric flow rate through the path (scfm),

A = flow area (leakage area) (ft^2),

ΔP = pressure difference across path ("w.g.),

K_f = coefficient, 2610 ("w.g./ft-min)

An initial estimate of leakage rate, including the vestibule doors and doors to the elevators was 4 ft^2. To obtain the objective of a pressure difference of 0.1" w.g. the calculated flow is 3,300 cfm. Using this as the base, a number of trial and error runs were made with the objective of

maintaining a minimum ΔP of 0.05"w.g. at each vestibule entry. The results indicate that an injection rate of approximately 3,000 cfm at each floor in 4 WTC and 4,000 cfm per floor in 5 WTC would be needed. Cases NELE-1A, NELE-1B, NELE-1C and NELE-1D cover these cases. The cases are based on an uncontrolled fire on one floor with a large number of windows on the windward side of that floor broken. One case in each building is based on winter conditions having an exterior temperature of 15° F and a wind impacting on the fire floor of 10 to 12 mph and another case where summer conditions of an exterior temperature is 90°F and no wind is present.

The calculated ΔP across the vestibule doors is shown in Table 6.8 All pressures are positive from the vestibule to the general building space. Since the intent is provide these spaces for the use of handicapped individuals, there is concern about the amount of force that will have to be applied to open the door to the "refuge area" once the smoke control air injection is initiated. Equation 4.18 from Klote and Milke (1992) was use to estimate the force involved for each of the cases. The equation is:

$$F = F_r + \frac{K_d W A \Delta P}{2(W - d)} \qquad \textbf{Equation 7}$$

where:

F = total door-opening force (lb),

F_r = force to overcome the door close and other friction (assumed to be 10 lb),

W = door width (assumed to be 3 ft),

A = door area (assumed to be 21 ft^2),

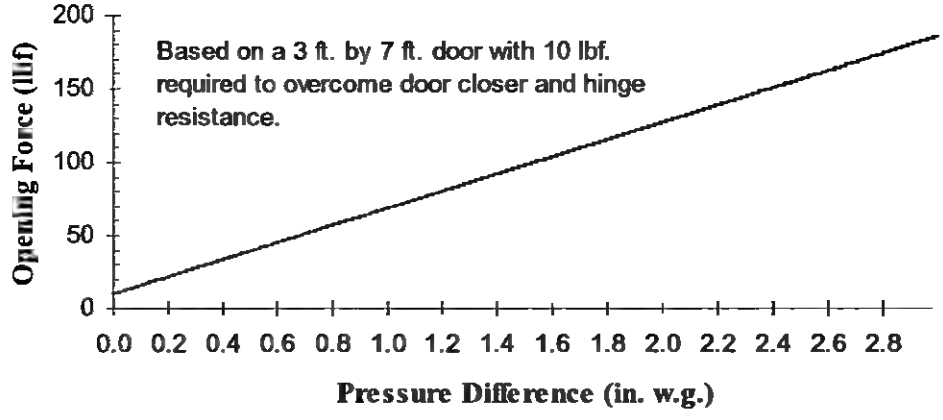
ΔP = pressure difference across the door ("w.g.),

d = distance from the doorknob to the knob side of the door (assumed to be 0.25 ft),

K_d = coefficient, 5.2. ($1/ft^2$-("w.g.).

The generic results of this calculation are shown graphically in Figure 9.

Figure 9. Door Opening Force



The calculated pressures and related opening forces for doors in 4 WTC and 5 WTC are shown in the following table.

Table 6.8. Calculated Pressure Differences and Door Opening Force for Elevator Vestibules

Case	Maximum		Minimum	
	Pressure ("w.g.)	Opening Force (lb)	Pressure ("w.g.)	Opening Force (lb)
NELE-1A 5 WTC, Winter conditions	0.30"w.g.	46 lb	0.12"w.g.	24 lb
NELE-1D 5 WTC, Summer conditions	0.24"w.g.	39 lb	0.19"w.g.	33 lb
NELE-1B 4 WTC, Winter conditions	0.28"w.g	42 lb	0.16"w.g.	29 lb
NELE-1C	0.17"w.g	30 lb	0.05"w.g.	16 lb

Some of the indicated opening forces are at level difficult for certain handicapped individuals to overcome. If this approach is used it may be necessary to provide barometric relief between the "refuge area" and the general building area to limit the over pressure involved to 0.05"w.g. to 0.1" w.g. (i.e., opening forces of 9 to 15 lb.)

6.9 Fire Involving a Passenger Car in the Parking Garage.

A fire involving a passenger car was simulated at both the B-1 and B-4 levels. Section 3.3.3 describes the expected fire from a passenger car under sprinkler protection. Cases NELC-1 and NELC-2 are the car fire simulations in which winter conditions were assumed and no smoke control action was taken.

In each case the fire was controlled without any significant smoke migration beyond the garage level of origin. With the fire simulated at level B-1 the smoke level in the garage eventually reduced vision to about 2,000 ft. With the fire simulated at the B-4 level, that smaller garage did suffer vision reduction to about 150 ft but no significant migration to other spaces occurred.

6.10 Fire in PATH Terminal

A tracer fire (simulating a steady fire of about 20,000 Btu/s) was simulated in the portal to the PATH terminal to trace the potential movement of smoke from a large fire in the PATH terminal. Cases NELP-1, NELP-2, NELP-3 and NELP-4 address fire in the PATH terminal. In the "as is" situation without any smoke control under winter conditions, smoke migrated through most of the Concourse and into the tower buildings. When all of the return fans for the Concourse were simulated as shut down, the direction of flow in the Concourse changed and smoke migrated to the north east portion of the Concourse and all floors of 5 WTC. When sufficient return flows were shut down in the towers to prevent flow from the Concourse into these buildings, the smoke flow was reversed into the PATH terminal. In this case the smoke was forced down into the PATH system. An additional simulation was made replacing the trace fire with the kiosk fire discussed in Section 3.3.5. With this controlled fire, the migration of smoke was limited to a level that reduced visibility to about 100 ft in the portal and the nearby areas in the Concourse.

6.11 Impact of Shutting Down HVAC Upon Detection of Smoke.

New addressable smoke detectors are being installed in the return air plenums in the tower buildings. At the request of the Port Authority an analysis was made of the impact of shutting down the supply and return fans serving the portion (quadrant) of the Floor where detection occurs. In such case the shut down would stop both supply and return service to all of the floors served by the MER that serves the floor where detection occurs.

Cases NEL-73, NEL-74, NEL-75 and NEL-76 address this issue. Case NEL-73 simulates the base case where no fans are shut down. The simulated source fire was the office workstation in a sprinkler protected space. No smoke migration outside the quadrant of fire origin was indicated.

In cases NEL-74 and NEL-75 the same fire was simulated. In NEL-74 it was assumed that the compartmentation for the fire quadrant of origin was complete. In NEL-75 it was assumed that the smoke was free to spread to all quadrants and as a result would shut down all of the HVAC to occupant spaces (i.e., perimeter supply, interior space supply and interior space return.) In both of these cases some smoke migrated through the duct work of the shut down HVAC systems. Case NEL-76 simulated an uncontrolled fire as discussed in Section 6.4 and all of the HVAC supply for the entire HVAC zone shut down. The results indicate smoke spread from 15th Floor to roof Level is expected with high carbon monoxide concentrations throughout the floors near the source. This is essentially the same spread that occurred in other cases involving an uncontrolled burnout fire without any smoke control efforts. (See Cases NEL-10, NEL-11, LAM-12A2, and LAM-13).

These analyses demonstrate that shutting down the fans results in leaving the now un-pressurized duct work available for smoke migration. The analysis indicates that a better practice would be to go to the core pressurization upon detection of fire.

6.12 Impact of Installing Revolving Doors on the World Financial Center Portal in One WTC Lobby

The Port Authority is considering the installation of revolving doors in the portal to the World Financial Center in the lobby of WTC 1. Presently the leakage between this portal and the

exterior is primarily determined by 6 doors. This portal was simulated in case NEL-4A to determine the expected flow under maximum stack effect conditions. (Defined as 15°F outside temperature with a 60 mph wind over the top of the building, with building HVAC systems set to Winter Normal.)

The amount of flow through the portal depends on the number of doors open. The CONTAM simulation was set to determine the flows and pressures estimated as entering WTC 1 from the portal and those entering from the Concourse to permit an analysis of the relationship of one to the other. In the simulation the six doors on the portal were progressively opened. As the area of opening increased, the pressure across the openings decreased and the flow from the portal into WTC 1 increased. At the same time, the flows into WTC 1 from the Concourse decreased. The flows and pressures determined by the model are shown in Table 6.12.

Table 6.12. Flows Into WTC 1 from Portal and Concourse

Number of Open Doors in Portal	From Portal to WTC 1		From Concourse to WTC 1	
	Pressure (in. w.g.)	Flow (cfm)	Pressure (in. w.g.)	Flow (cfm)
1	0.78	26,000	0.77	124,000
2	0.69	52,000	0.73	120,000
3	0.64	75,000	0.69	111,000
4	0.60	95,000	0.65	107,000
5	0.56	114,000	0.62	103,000
6	0.53	132,000	0.58	100,000

The flow through the portal is concentrated in a single stream while the flow from the Concourse is divided among the 14 revolving doors, two handicapped doors, and the joint leakage's in the partition between WTC 1 and the Concourse.

Assuming that the leakage rates through six revolving doors and the associated partition would be approximately equivalent to that through a single open door, Table 6.12 illustrates that the installation of revolving doors in the portal could result in an increase in the present flow into

WTC 1 from the Concourse by about 25% (from 100,000 cfm with six doors open to 124,000 cfm with revolving doors at the portal). This would increase the flow of smoke from a fire in the Concourse into WTC 1.

The recommendations in this report are, however, based on the worst case (i.e., all portal doors closed) since 2 WTC does not have a similar portal. This case represents the worst case since the flows into the lobby from the Concourse will be highest when the pressure differences across the barrier are the highest. Therefore, the installation of revolving doors would not make a significant impact on the flow of smoke from the Concourse into the lobby of 1 WTC. The installation of such doors would however reduce the overall stack effect in 1 WTC by increasing the resistance to infiltration into the building.

From the standpoint of smoke management, the presence or absence of revolving doors at the portal is a minor factor that does not change the overall smoke management approaches recommended. It may however, be desirable to install the doors since they would cut down on the infiltration into the building somewhat.

6.13 Egress Times and Exposure to Carbon Monoxide

The time to egress is based on the approaches detailed by Nelson and MacLennan (1995). In these buildings the time to egress is dominated by the throttling effects of the exit doors from the stairways. In each of the towers there are 3 stairs each having one 36 inch exit door. In 5 WTC there are 3 set of double stairs with each set having 2 exit doors for a total 6 exit doors. In 4 WTC there are two double and one single stairs with a total of 5 exit door from these stairs. The Port Authority indicates that the approximate population of the towers is 20,000 persons in each tower. A population of 20,000 persons in a tower building represents at population density of approximately 200 ft^2/person. Applying this same density to 4 WTC and 5 WTC yields an estimated population, that would use the stairs for exit of about 2400 persons in 4 WTC and 2600 persons in 5 WTC.

The flow capacity of a 36 inch wide door is approximately 50 persons per minute when used to its maximum capacity (Nelson & MacLennan, 1995). Based on the preceding the minimum time to egress the several building would be approximately as shown in Table 6.13.

Table 6.13. Minimum Exit Times

Building	Population	Number of Stair Exit Doors	Time to Egress through Exit Doors (min)
1 WTC	20,000	3	133 min
2 WTC	20,000	3	133 min
4 WTC	2,400	5	10 min
5 WTC	2,600	6	8 min

Experience in office buildings (Nelson & MacLennan, 1995) indicates that the actual egress time is always greater than the minimum exit time. This extra time is that used by factors such as investigation or query into the meaning of the alarm resulting in delayed start of egress, inefficiencies in using the stairs, and other factors. For buildings with an organized evacuation plan such as the WTC Complex, Nelson & MacLennan recommend that the actual expected egress time be assumed to be double the calculated minimum time. For purpose of estimating time that might be required for the last person to leave the building, a design time of 4 hours has been used for the tower building and 20 min for both 4 WTC and 5 WTC.

Depending on the size and location of the fire, persons evacuating one of the office building may be exposed to smoke and gases produced by that fire. The principle toxic species being carbon monoxide (CO). Tables 6.13 A, B, and C show the extent of exposure to be expected by persons using the stairways to exit the building. The levels are based on the calculated entry of smoke and gases into the stairwell during the time required to egress the building. The analysis makes the conservative assumption that at least one person may be within the stairwell for a period of time approaching the entire building egress time.

Table 6.13 A. Impact of CO exposure during evacuation from 1 or 2 WTC.

Smoke Control Approach	Maximum Carbon Monoxide Exposure in exit route (ppm)	Approximate Average Carbon Monoxide in Exit Route During Egress (ppm)	Potential Accumulated COHb (%)
Case NEL-11 Uncontrolled fire, 9th floor, Windward windows broken, No smoke control	11,000	1,215	> 50 (226) (Stairs potentially lethal)*
Case NEL-12 Sprinkler protected office fire, 9th floor, No smoke control	7	<1	<1
Case LAM-49 Uncontrolled fire, 55th floor, Windward windows broken, Positive pressure ventilation smoke control on.	None (No smoke migration into any exit route or off of floor of fire origin)	None	None

* This calculated value using Equation 2 does not consider human limitations. The indicated high concentration of COHb is a physiological impossibility, but shows that lethal conditions will develop in much less time than the expected egress time.

Table 6.13. B Impact of CO exposure during evacuation from 4 WTC.

Smoke Control Approach	Maximum Carbon Monoxide Exposure in exit route (ppm)	Approximate Average Carbon Monoxide in Exit Route During Egress (ppm)	Potential Accumulated COHb (%)
Case NELA-57 Uncontrolled fire on 8th floor, Windward windows broken,	28,000	1,442	35 (incapacitating) Smoke migrates into southeast portion of Concourse
Case NELA-60 Sprinkler protected office fire, 8th floor, No smoke control	None (No smoke migration into any exit route or off of floor of fire origin)	None	None
Case NELS-63D Stair pressurization	None	None	None

Table 6.13. C Impact of CO exposure during evacuation from 5 WTC.

Smoke Control Approach	Maximum Carbon Monoxide Exposure in exit route (ppm)	Approximate Average Carbon Monoxide in Exit Route During Egress (ppm)	Potential Accumulated COHb (%)
Case NELA-51 Uncontrolled fire on 4th floor. No smoke control	7800	5000	91 (lethal)* Smoke migrates through Concourse and into towers
Case NELA-60 Sprinkler protected office fire, 8th floor, No smoke control	None	None	None
Case NELS-63A Stair pressurization	None	None	None Smoke migrates through Concourse and into towers

* This calculated value using Equation 2 does not consider human limitations. The indicated high concentration of COHb is a physiological impossibility, but shows that lethal conditions will develop in much less time than the expected egress time.

As discussed in Section 2.0, Tenability, the criteria for acceptable CO exposure was set at 12% COHb. Purser (1995) sets the basis for incapacitation from CO exposure at about 30% COHb saturation in the blood stream, and death for healthy individuals at 50% COHb saturation. Both the incapacitation and lethal levels are believed to be lower in persons with compromised cardiac function. The use of the 12% criteria provides a safety factor for both such vulnerable persons and for the uncertainties in the prediction of the actual rate of CO generation in any fire.

The weather conditions for each of the case simulated for Tables 6.13.A, B and C was 15° F outside temperature with a 10 mph wind at grade and a 60 mph wind across top of building.

6.14 Relevance to NYC Building Code and NYC Fire Department Requirements.

The smoke control measures proposed in this report are in line with the requirements of Section 4-2, Smoke Control - Special Situations, of NYC Building Code Reference Standard Reference RS 13, Mechanical Ventilation, Air Conditioning and Refrigeration Systems. Specifically the approaches in this report are felt to meet the requirements of Section 4-2 that reads:

> A building ... in which it is determined that evacuation time is excessive ... shall have the duct systems arranged so that, in the event of a fire, flow of smoke from the fire zone will be inhibited from spreading to required interior ways of exit access, interior enclosed stairs and ramps, interior exit passageways and designated refuge areas. Such an arrangement may involve air conditioning systems alone or in combination with other systems such as emergency venting and fire suppression, taking into account stack and wind effect of multistory buildings. Smoke control systems are required to be engineered for the specific occupancy and building design.

The justification for the smoke control approaches proposed in this report are based in the above requirement.

A second issue is the desire of the NYC Fire Department that the activation of smoke control measures not be initiated until so ordered by the fire officer in command at the time of a fire. This report proposes that the initial smoke management action, core pressurization in the towers,

pressurization of the tower basement area if smoke from a truck dock fire is detected within the tower perimeter, and stairwell pressurization for 4 WTC and 5 WTC be initiated as soon as a fire is detected. It is our opinion that this early response of these smoke control efforts is necessary for the best level of occupant safety and needed to conform with Section 4-2 of Reference Standard 13, as quoted above. It is also our analysis that the amount of air movement at this stage of smoke control is insufficient to affect the rate of burning.

This report proposes a second emergency level of smoke control involving positive pressure ventilation. This level is to be used only if an uncontrolled fire has reached such proportions that windows are being broken out by the fire and then only with the concurrence of the fire officer in command. This approach, of course, is in concurrence with the Fire Department's desires.

7.0 Conclusions

As a result of the analyses conducted, the following conclusions are drawn.

1. Sprinkler Protection

The analysis in this project along with those in the previous project, Smoke Management Evaluation Study of The World Trade Center Concourse and Plaza (Hughes, 1996) show that, with the several exceptions noted herein, the provision of sprinkler protection will allow only minor smoke migration from the space of fire origin. All of these analyses of sprinklered fires indicate that exit paths, stairs and elevators will remain sufficiently free of smoke to be safely used for building egress. In these cases, persons proximate to the fire may have to evacuate the space of fire involvement but can find safe refuge in the core area or on an adjacent floor.

2. Stairwell Protection in Towers

As discussed in Section 6.5.1, the height of the towers and the tower stairwells precludes effective traditional stair pressurization of major portions of the stairs by air injection. The protection of the stairs from smoke intrusion can be accomplished, however, by core pressurization in the expected cases and by positive pressure ventilation in the unlikely event of an uncontrolled fire. See Section 6.4.

3. Core Pressurization Smoke Control in Towers

The vast majority of anticipated fires in the towers will be small and controlled by the sprinkler system. In these cases, setting the HVAC systems to the Core Pressurization configuration (See Figure 6) will contain the smoke in the area of fire origin, and prevent the spread of dangerous levels of smoke and contaminants into the core, the stairwells, and the elevator shafts.

4. Positive Pressure Ventilation of Towers

As noted in the analysis, it is possible to hypothesize a fire of major magnitude that could involve an entire floor in one of the Towers. Such fires have occurred in office buildings without sprinkler protection, but to date we are unaware of any that have occurred in a sprinkler protected office facility. A fire involving an entire floor was used in this study to assess the potential of developing smoke management systems capable of withstanding the most severe exposure.

In the unlikely event that an uncontrolled fire develops, it is possible to use the HVAC fans to provide smoke control for the tower buildings, once that fire breaks out windows. The approach involves positive pressure ventilation. (See Figure 7) This approach as described in Section 6.4.1 is designed to keep both stairwells and elevators clear of smoke and toxic gases. The use of these fans under these conditions can result in pressures on the fire floor stairwell doors that would prevent any persons still on that floor from escaping. It should never be used until that floor is clear of occupants, and only under the direction of the fire officer in charge of the incident.

5. Stairwell Smoke Control, 4WTC

In 4 WTC it is possible to use air flow, either provided by dedicated fans or diverted into the stairwell from the building system, to pressurize the stairwells sufficiently to exclude smoke from the severe winter fire condition described above. This can be accomplished while not over-pressurizing the stairs.

6. Stairwell Smoke Control, 5 WTC

In 5 WTC is possible to use air flow as in 4 WTC to pressurize the stairwells. However, the air flow needed to provide for pressurization with up to 3 doors open can over-pressurize the doors when all of the doors are closed. For such a system to work in 5 WTC, it will be necessary to provide a nearly instantaneous pressure control device, such as barometric dampers. This is necessary to assure sufficient pressure when doors are open and prevent over pressurization when all doors are closed.

7. Smoke Control for Elevators, 4 WTC and 5 WTC

In both 4 WTC and 5 WTC there are vestibules outside the entrances to the freight elevators on each of the office floors. Simulations using air flow to pressurize these vestibules indicated that it is feasible to use air injection into these spaces to provide "areas or refuge" for handicapped individuals to be removed from the building via these elevators. In 5 WTC, the model indicates that it is necessary to inject 4,000 cfm into the vestibule on each floor. In 4 WTC, the model indicates that it is necessary to inject 3,000 cfm into the vestibule on each floor.

8. Smoke Flow into Concourse

If the hypothesized severe winter fire occurs in 5 WTC, the analysis indicates that the smoke will spill out of that building into the Concourse and across the concourse into the tower buildings. The analysis indicates that this flow can be restrained if one of the following options is employed:

a) The entire concourse and the towers are placed in a pressurization mode by shutting off the return and exhaust fans serving the Concourse and a sufficient number of return fans in the Towers to prevent flow from the Concourse into the Towers, or

b) Install doors that will be closed at the time of a fire to separate the Concourse and Plaza level entrances from 5 WTC to the Concourse, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8, or

c) Install doors that will be closed at the time of a fire on the escalator, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8.

Option (a) will confine the smoke to the floor of origin, keeping the exit routes clear throughout the fire. Options (b) and (c) will permit smoke migration into the lobbies on all floors below the fire floor, with some migration into the adjacent area of the Concourse, but the exit routes will remain clear.

9. Fire in PATH Terminal

A minor, sprinkler controlled, fire in the PATH terminal would result in local smoke and minor spread to those portions of the Concourse nearest the PATH entrance. In case of a major fire in the PATH terminal, without either sprinkler suppression or smoke control, smoke would spread widely over the entire Concourse and into the tower buildings. To prevent this it would be necessary for the entire Concourse to be placed in a pressurization mode, by shutting down return and exhaust fans serving the Concourse and adjusting the fans in the towers to prevent air flow from the Concourse into the towers. If this were done, however, the smoke from the fire would be forced into the PATH terminal and system.

10. Truck Fire at Loading Dock

If a fire develops in the cargo compartment of a large truck, shielded from the garage sprinkler protection, a serious condition of smoke migration into the adjacent tower can occur. With the combination of open loading dock doors and no smoke control in the tower, smoke can spread into the B-1 level. With the loading dock doors closed and the sub-grade levels and the lobby return fans off, smoke can be controlled, even on a severe winter day. The loading dock doors should be kept closed or arranged to close automatically in the event of a fire.

11. Tower Lobby Fire

The lobby HVAC system has the capabilities to be used as an atrium smoke control system to keep the exits through the lobby of a tower passable given a large (11,000 Btu/s) fire in the lobby. Under severe winter conditions it would be necessary to shut down sufficient supply fans in adjacent zones to prevent stack effect flows up the elevators from diverting smoke into the elevator shafts.

12. Passenger Car Fire in Garages

A fire involving a passenger car in the garage would not result in significant smoke migration into the adjacent buildings or obstruct egress from the garages.

13. Impact of Shutting Down Fans Upon Smoke Detectors

Shutting down fans on smoke detection is less effective in terms of smoke control than leaving the fans on and spilling all of the return and setting the supply on 100% outside air.

14. Interrelationship of All Elements of WTC Complex

The analyses in this project re-enforce the fact that all of the HVAC systems in the entire complex interact significantly. Any major changes in one portion of the facility may impact other portions of the facility, potentially affecting the movement of smoke from a fire. The most significant impact is that produced by the PATH system on the Concourse and 5 WTC. Other impact could result if separate sections of the complex, such as one or more office building, were placed under separate HVAC management from the complex as an entity.

8.0 Recommendations

As the result of this study, the following recommendations are submitted.

1. ***Sprinkler Protection (Entire Complex)***

   Complete the program for total automatic sprinkler protection of the entire complex. Where spaces are known to be used for storage or track files or other high concentrations of potential fuel for a fire, provide extra protection in the form of additional suppression capabilities (i.e. increased discharge density from the sprinkler system), fire resistive enclosure of the space involved, or both.

2. **Emergency Smoke Management Sequence in Tower Buildings**

   The following sequence of actions is recommended in case of a fire in one of the towers.

   a) Notify the NY City Fire Department and follow the WTC emergency procedures for the floor involved and adjacent floors.

   b) Upon activation of any smoke detector or sprinkler system, set the HVAC system covering the entire zone where the fire is detected to core pressurization.

   c) If smoke detectors involving 2 or more detectors on floors other than the fire floor occurs, evacuate all floors served by the MER serving the fire floor that are on the same side of the MER floor as the fire floor; that is all floors served by the same supply fans that serve the floor of fire involvement.

3. **Handling An Uncontrolled Fire in a Tower**

   While an uncontrolled fire is an unlikely event, it is prudent to provide contingency plans for smoke protected egress and refuge in case of such an event occurs. Plans to institute positive pressure ventilation as described in Section 6.4.1 should be developed and coordinated with the New York City Fire Department and regularly rehearsed and tested. Implementation of positive pressure ventilation by its nature is a fire ground action and would be implemented

under the direction of the fire officer in charge with advice and assistance from the WTC engineers.

4. Smoke Control for Stairs and Elevators, 4 WTC and 5 WTC

It is recommended that pressurized smoke control be considered for the stairs and the freight elevator vestibules in 4 WTC and 5 WTC. (i.e., a dedicated fan system injecting air at multiple points in the stairs and into the vestibules each floor.) As discussed in the analysis, barometric relief or other pressure relief will be needed in the stairs for 5 WTC. The recommended operating sequence is to initiate the Stair and vestibule pressurization upon activation of more than one detection of smoke in the plenum space. To lessen the circulation of smoke through the HVAC ducts, the HVAC system should not be shut down but set to total outside air with no recirculation.

5. Additional Area of Refuge Design Elements, 4 WTC and 5 WTC

The pressurization of the freight elevator vestibules is intended to provide the basis for "areas of refuge" for handicapped persons. If the Port Authority elects to use these vestibules for this purpose it will be necessary to:

a) Equip all of the vestibule doors with door closers triggered by the activation of the smoke control system.

b) Provide the necessary signage and communications system to identify the spaces as areas of refuge and enable anyone in the areas of refuge to communicate their location and needs to the WTC emergency control location.

c) Recall the elevators serving the vestibules to the exit floor and place them in emergency service. The accessible egress paths usable by a mobility impaired person is via the elevators serving these vestibules exiting at the Concourse or B-2 levels. Both of these routes are potentially exposed to blockage by smoke, though the likelihood of both being blocked is improbable, as demonstrated by the analysis in this report. For this reason it will be necessary to know the condition of the egress routes before evacuating anyone using the elevators. Evacuation should then be

controlled by an emergency operator who is aware of any smoke in the exit routes and can act accordingly.

6. Keeping Smoke Confined to 5 WTC

A special problem exists in case of a severe fire in 5 WTC. If, in event of fire, the smoke detectors indicate smoke in three or more smoke detection zones, it is possible that a fire overtaxing the sprinkler system has occurred. In this case there is a danger of smoke spreading into the Concourse and tower buildings. To counter this, if such a warning occurs, all of the returns from the Concourse HVAC systems should be shut down. If such a fire occurs under winter conditions, return fans in the towers will also have to be shut down to keep smoke within the perimeter of 5 WTC. Other approaches to controlling the smoke from a fire in this building were modeled (See Section 6.4.2), but none exhibited the same level of safety in 5 WTC and the Concourse open to it.

7. PATH Terminal

The Port Authority needs to continue its studies of smoke management in the PATH terminal. A minor, sprinkler controlled fire in the terminal would not present a serious hazard. A major fire, typified by a PATH car fire could, however, expel smoke into the Concourse, migrating either into the towers or into 5 WTC. The smoke could be held back by shutting down all Concourse return fans and sufficient return fans in the towers so that air flow is from the tower lobbies into the Concourse. If this were done, however, the smoke would be forced into the terminal and the PATH system itself. We understand that Port Authority Engineering has completed a preliminary design for the PATH Terminal smoke management system that is compatible with the criteria, assumptions, and findings of this study.

8. Interrelationship of PATH Terminal and Complex

It is important, however, that no solution that involves the closure of the PATH terminal from the Concourse be considered without evaluation of the effect of that closure on smoke movement in the Concourse. The PATH terminal is a major source of air that avoids a winter condition where the towers could impose a negative force on 4 WTC and 5 WTC.

9. Loading Dock Smoke Control

Damage to the doors between the loading dock and the tower building should be repaired. The rolling steel doors should be equipped with smoke detectors, arranged to close these doors if they should be open and a fire occurs at the dock. Additionally, if two or more smoke detectors in the return air from the B-1 space are activated, the supply to the sub-grade portions of the tower involved and the supply to the lobby of that tower should be shut down.

10. Tower Lobby Smoke Control

In case of fire in the lobby of one of the towers, the lobby supply and return should be continued in operation with no recirculation and 100% fresh air supply and 100% exhaust of the return. In winter conditions the core returns for floors 1 to 6 and sub-grade areas should be shut down. Additional returns should be shut down until any flow from the concourse or outside into the lobby is mitigated. To implement this it is recommended that a pressure sensors be installed in each of the tower lobbies that measure the pressure difference between the lobby and the Concourse and between the lobby and the exterior. The data from these reading should be shown in the control room.

11. Further Tests

Tests of the proposed procedures should be conducted under both summer and winter extreme conditions prior to implementation of this study to verify the pressures predicted by the model. The procedures recommended above are based on calculations using the model CONTAM96. As such they involve the use of selected field measurements and assumptions relative to specific leakage paths and dimensions. It is felt that pressure differentials and pressures applied to doors in the means of egress are the key measurements. The use of smoke tracers, while not considered essential, could be of assistance in discovering unanticipated leakage paths.

9.0 References

ASHRAE, 1989

ASHRAE Handbook - Fundamentals, American Society for Heating Refrigeration and Air Conditioning Engineers, Atlanta, GA, 1989.

Babrauskas, 1995

Babrauskas, Vytenis, "Burning Rates," Chapter 3-1, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

BHP, 1987

BHP Melbourne Research Laboratories, "Fire in Closed Carpark Buildings," BHP Melb. Res. Lab. Rep. No. MRL/PS98/87/001, September, 1987.

Caro, 1995

Caro, Tony C., and James A. Milke, "A Survey of Fuel Loads in Contemporary ONice Buildings," University of Maryland Department of Fire Protection Engineering, for NIST, November, 1995.

ECCS, 1993

European Convention for Constructional Steelwork, Technical Committee on Fire Safety, "Fire Safety of Open Car Parks," Technical Note No. 75, Draft, March, 1993.

Hughes, 1996

Hughes Associates, Inc., and Dillon Consulting Engineers, Inc., "Smoke Management Evaluation Study of the World Trade Center Concourse and Plaza," Port Authority of New York and New Jersey, May, 1996.

Klem, 1991

Klem, Thomas J., "High-Rise Fire Claims Three Philadelphia Fire Fighters," *NFPA Journal*, September/October 1991, p. 64.

Klote and Milke, 1992

Klote, J.H., and Milke, J.A., *Design of Smoke Management Systems*, American Society for Heating Refrigeration and Air Conditioning Engineers, Atlanta, GA, 1989.

Lougheed, 1996

Lougheed, G. D., personal communication.

Lougheed, 1994

Lougheed, G.D., J.R. Mawhinney, and J. O'Neill, "Full Scale Tests and the Development of Design Criteria for Sprinkler Protection of Mobile Shelving Units," *Fire Technology*, **30** (1), 1994, pp. 98-133.

Madrzykowski, 1992

Madrzykowski, Daniel, and Robert L. Vettori, "A Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System," NISTIR 4833, National Institute of Standards and Technology , May, 1992.

Mangs, 1994

Mangs, J., and O. Keski-Rahkonen, "Characterization of the Fire Behavior of a Burning Passenger Car. Part I: Car Fire Experiments," *Fire Safety Journal*, **23**, 1994, pp. 17-35.

Mitler, 1996

Mitler, H. E., The Burning of a Merchandise Kiosk," National Institute of Standards and Technology. (Personal communication, report to be published.)

Mulholland, 1995

Mulholland, George W., "Smoke Production and Properties," Chapter 2-15, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Nelson and Forssell, 1994

Nelson, H.E., and Forssell, E.W., (1994), "Use of Small Scale Tests in Hazard Analysis," *Fourth International Symposium on Fire Safety Science, International Association for Fire Safety Science*, 1994, pp 971-982.

Nelson and MacLennan, 1995

Nelson, H.E., and MacLennan, H.A., "Emergency Movement," Chapter 3-14, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Nelson, 1989

Nelson, Harold E., "An Engineering View of the Fire of May 4, 1988 in the First Interstate Bank Building, Los Angeles, California," NISTIR 89-4061, National Institute of Standards and Technology, March, 1989.

Nelson, 1989

Nelson, Harold E., "An Engineering Analysis of Fire Development in the Hospice of Southern Michigan, December 1985," Fire Safety Science-Proceedings or the Second International Symposium, 1989.

Nelson, 1990

Nelson, Harold E., "FPETOOL: Fire Protection Engineering Tools for Hazard Evaluation," NISTIR 4380, National Institute of Standards and Technology, March, 1990.

Purser, 1995

Purser, David A., "Toxicity Assessment of Combustion Products," Chapter 2-8, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Shipp, 1995

Shipp, Martin, and Michael Spearpoint, "Measurements of the Severeity of Fires Involving Private Motor Vehicles," *Fire and Materials*, 19, 1995, pp. 143-155.

Tamura, 1994

Tamura, George T., *Smoke Movement and Control in High Rise Buildings*, National Fire Protection Association, Quincy, MA, 1994.

Tewarson, 1995

Tewarson, A., "Generation of Heat and Chemical Compounds in Fires" Chapter 3-4, *Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Appendicies

Appendix A

CONTAM 96

Theory and Validation

APPENDIX A. Table of Contents

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Note: This material is abstracted from the CONTAM 93 user manual, document NISTIR 5385, published by the National Institute of Standards and Technology. The CONTAM 93 user manual is authored by George N. Walton. CONTAM 96 is an updated version of CONTAM 93 and CONTAM 94, with some new features included, but the CONTAM 93 documentation contains the relevant background material. The single most important improvement to the program is the ability to handle larger models. Without this improvement, the Tower Model constructed for this report would have been considerably less sophisticated.

1. INTRODUCTION

1.1 Background

The National Institute of Standards and Technology (NIST) has over the past several years developed a series of public domain computer programs for calculating air flow and contaminant dispersal in multizone buildings. The most recent of these is NBSAVIS/CONTAM88 (Grot, 1991).

There are several applications for building airflow calculations. The earliest such NIST (then NBS, the National Bureau of Standards) program was ASCOS (Analysis of Smoke Control Systems) (Klote, 1981, 1983). Another program, TARP (Thermal Analysis Research Program) (Walton, 1983, 1984), used multizone airflow calculations to estimate the portion of building thermal load due to infiltration and perform a simple contaminant migration analysis. Programs were developed specifically for the study of contaminant migrations (CONTAM86 and CONTAM87, Axley, 1986, 1988). Improvements in the algorithm for computing airflows were described in the AIRNET program (Walton, 1989).

All of these programs take the multizone network approach to airflow analysis. That is, the building is treated as a collection of zones connected by airflow paths. These zones may represent groups of rooms, individual rooms, or even portions of rooms, as well as shafts and portions of the building air handling system. Within each zone the temperature and contaminant concentration is considered to be uniform. The airflow paths include doorways, small cracks in the building envelope, and a simple model of the air handling system. This approach is a compromise between the single-zone building model, which is appropriate only for the simplest of buildings, and computational fluid dynamics models, which are still too time consuming for use on a regular basis, especially for large buildings.

Use of these programs has indicated that the computational algorithm in ASCOS needs to be replaced by a faster and more robust algorithm such as used by AIRNET, while the AIRNET user interface which was designed for research purposes needs to be replaced by a much more easily used interface. It was decided to combine the best available algorithms with a graphic interface in a program usable on commonly available small computers. This program is called CONTAM93.

1.2 Purpose

The purpose of this effort was to develop an easily used contaminant analysis program using a graphic interface with the contaminant simulation capabilities of CONTAM88 and the airflow analysis method of AIRNET.

1.3 Scope of report

The following sections of this report contain a general description of CONTAM93, a description of the contaminant dispersal and airflow calculation algorithms, and some necessary details on the computational environment. The appendices give a detailed description of the user interface.

2. GENERAL DESCRIPTION

CONTAM93 is an easily used contaminant analysis program with the contaminant simulation capabilities of CONTAM88 (Grot, 1991) and the airflow analysis method of AIRNET (Walton, 1989).

CONTAM93 requires a 286 class (or higher) PC compatible computer with math coprocessor. VGA graphics, and MS-DOS. CONTAM93 consists of two programs: CONTAM and CONTAMX. CONTAMX is a non-interactive program which computes the airflows and contaminant dispersal. CONTAM is an interactive program for processing the CONTAMX input and output files. Both CONTAM and CONTAMX operate under the 640K-byte memory limit of MS-DOS, but this still leaves room for simulating some very large buildings.

CONTAM93 is designed to simplify the data input and analysis processes for a multi-zone airflow and contaminant dispersal simulation. It is still up to the user to determine what processes are important and how the complexities of a building can be abstracted into the mathematically computable model used by CONTAM93. A lengthy data gathering process may be required.

The user does not directly access the data files describing the building. All access is done through the CONTAM program and its graphic interface. The main portion of the computer screen will be occupied by the "SketchPad" or a data entry screen as described below. The options area to the right indicates possible actions that can be taken by pressing the keys indicated. The status area at the bottom of the screen displays information about the current object on the SketchPad, error messages, and questions. The screen interface is explained in detail in the appendices.

The description of the building is created (or modified) in the SketchPad. The SketchPad consists of an array of small cells into which the user places various symbols representing building features relevant to the calculation of contaminant dispersal. This produces a simple illustration which has been chosen intentionally to represent the simplicity of the underlying mathematical model. The SketchPad is used to establish the geometric relationships of the relevant building features. It is not intended to produce a scale drawing of the building. It is used to create a simplified model where the walls, zones, and air flow paths are topologically similar to the actual building. Engineering judgement must be used to define this model of the building. The SketchPad allows the entry and display of the data in an intuitive manner. The SketchPad will bring up various data entry screens needed to define the mathematical characteristics of the various building features.

Building data is organized by "levels" with data entry beginning at the lowest level. A level would typically be a building floor, but a suspended ceiling acting as a return air plenum or a raised floor acting as a supply plenum may also be treated as a level leading to multiple levels per floor. Define the walls first. "Walls" are used to separate regions of uniform air, called zones, on a given level. Such walls include the building envelope and internal partitions with a significant resistance to air flow. Walls must be drawn to create enclosed regions (zones). There is a set of implicit walls (actually floors) separating the zones on different levels. Identify the zones next. A "zone" indicates a volume of air with uniform temperature and contaminant concentration. Zones are defined on the SketchPad as a region surrounded by walls. Every zone must be identified. A default ambient zone surrounds the building. An airflow path indicates some building feature by which air can move from one zone to another. Such features include cracks in the building envelope, open doorways, and exhaust fans. Path symbols placed on the walls are used to represent openings between zones or to ambient; any other placement represents an opening in the floor to the zone on the level below. Contaminant source (or sink) symbols may be placed in any zone. These represent any feature (within the list of available models) which produces or removes a contaminant. A simple model of an air handling system is available with supply and return point

symbols placed within the appropriate zones.

Figure 1 shows one level of a building with lines representing the walls that define the zones, and diamond shaped symbols representing the airflow paths between zones. As you move the cursor across zone and path symbols, summary data is displayed on the screen. Pressing the enter key while at a zone, path, of contaminant symbol gives access to the complete data and permits you to change the data. Other keys allow you to copy, move, or delete various symbols. A model of a multi-level building is built one level at a time. Since levels in tall buildings tend to be similar, the user can create a level by copying a lower level and editing the SketchPad display.

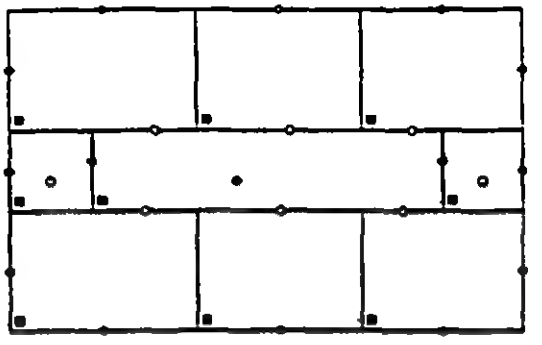

Figure 1. SketchPad Example

In addition to the relationships established on the SketchPad, a great deal of numeric data is required to define the mathematical model for the simulation. This data is prepared in the data entry screens. A data entry screen consists of one or more data entry fields and accompanying text. The data entry fields are generally organized with the most important data toward the top of the screen. A more detailed explanation of the data entries is available from the on-line help procedure. Default values are often provided. Reminders about how to use the data entry screen are provided in the options window to the right. There are several different types of data entry fields. They allow an action to be taken, a choice made, a name given, or a numeric value specified. Data entries representing physical values also have the units displayed in brackets, e.g. [m^2]. The user can change the units. In order to minimize the amount of numerical data entered, data representing a single building feature, such as a doorway, is grouped together and given a name by the user. When that feature is needed at another place in the building, it can be referred to by name instead of re-entering all the numeric data.

Once the building description is complete, the user may select one of several simulation modes to be done by CONTAMX. Steady, transient (up to 24 hours), and cyclic (24-hour steady-periodic) contaminant simulations are possible. Steady or dynamic (transient / cyclic) calculation of the airflows may be done. The results of the simulation can be graphically viewed with CONTAM using the SketchPad display. The display shows the pressure drops and flow rates for the airflow paths. The zone contaminant concentrations can be displayed by moving the cursor to a zone symbol. For transient simulations, concentrations, each normalized for the peak value, are presented graphically. The user may also create files which can be printed or used in other applications. The zone and path file uses a format similar to the one used by the ASCOS program. The contaminant data is printed in two different formats based on whether a steady or transient simulation was done.

The building descriptions created with CONTAM are saved in project data files. These files must be saved to keep a record of what was simulated. The various reports provide only the results of simulation, not the building description. A research or design project will usually involve several different project files describing different conditions from which comparisons and choices will be made.

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Smoke Management Evaluation Study of The World Trade Center Complex Excluding the Concourse and Plaza

Draft Final Report

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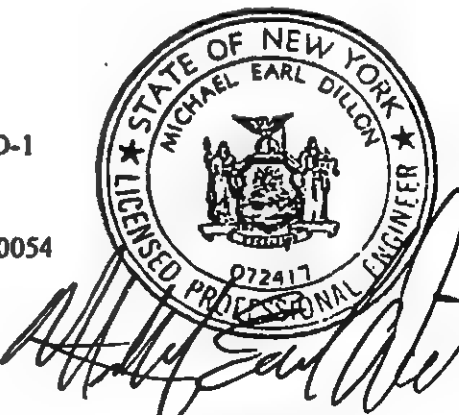

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Executive Summary

This is a report on the Smoke Management Evaluation Study of the World Trade Center Complex, excluding the concourse and plaza levels which were studied under an earlier report (Hughes, 1996).

The evaluation of the smoke management system and the development of alternative smoke management were undertaken as an engineering analysis based on the physics of fire, smoke development, automatic sprinkler response, and smoke flow. Various engineering equations and models were used as described in Section 2 of this report. Major use was made of the mass movement network model CONTAM 96. The model, its validation, and its use in this project are discussed in Section 2 and documented in the several report appendices.

The objectives of this project are to evaluate the existing HVAC and smoke management systems for the four office buildings (WTC 1, 2, 4, and 5) and the sub-grade areas of the WTC complex, and to determine the ability of these systems to perform effectively in the event of a fire or smoke condition. Based on the evaluations conducted, recommendations for future smoke management design are provided.

The criteria followed were based on the protection of the building occupants. from intolerable smoke conditions during the course of a fire and their egress from the building. Conditions were considered to be intolerable in any space where the visibility dropped below 200 ft. or the amount of carbon monoxide (CO) present in the space was sufficient to cause a CO blood saturation (carboxyhemoglobin) level exceeding 12 percent throughout the anticipated exposure time.

The length of time that an occupant can be exposed to the smoke, if present, is a function of the time required for that individual to egress the building, or the space in the building where the smoke is present. In the Towers, the rate of egress is eventually controlled by the exit doors from the stairwells. The maximum rate of flow through such doors is between 50 and 60 persons per minute per door (Nelson and MacLennan, 1995). Based on an expected population of 20,000

persons per tower building, the minimum egress time is about 2 hours to clear the entire building. Given an average population of 200 persons per floor, they can clear the floor and enter the stairwells in one to three minutes depending on the length of delay in starting evacuation. On this basis the evacuation of three floors to a safe floor below can be accomplished in about ten minutes, depending on the length of time between notification and start of egress.

Based on an expected population of 2,400 in WTC 4, the minimum egress time is about 10 minutes. Similarly, based on an estimated population of 2,600 in WTC 5, the minimum egress time would also be about 10 minutes.

The preceding evacuation time estimates do not include consideration of likely delays in starting egress and various inefficiencies in the use of the exit routes. For design purposes, the estimated actual egress time was assumed to be double the calculated minimum (Nelson and MacLennan, 1995), that is 4 hours for the towers and 20 minutes for 4 WTC and 5 WTC.

Smoke Hazard Potential

This analysis is based on fire safety conditions as they will exist once the program to provide sprinkler protection throughout the entire complex is completed. The provision of sprinkler protection is an ongoing program, currently tied to space renovation and is reportedly between 80 and 90 percent complete in the office buildings.

The current plenum smoke detectors are being replaced with a system of addressable smoke detectors. This will reduce the potential of false alarm and increase the ability to trace the movement of smoke from a fire.

For virtually all fire situations the sprinkler system will control the fire and the smoke can be confined to the space of origin by switching the HVAC system to "Core Pressurization". [1]

The exception of concern is the extremely unlikely but still remotely possible involvement of an entire floor or major portion of a floor in a fully involved fire. The fire used to model this condition is referred to in this report as an "Uncontrolled Fire." Such fires have occurred in other office buildings, and are discussed in greater detail in Section 3.3.2. If such a fire were to occur on any office floor in one of the towers and special smoke control measures were not taken, the results could be disastrous to those in the building involved, spreading potentially lethal smoke through the building faster than the buildings can be evacuated. The potential is most severe in the tower buildings because of the long time required to exit these buildings. (See Section 6.12.)

The source of such an "uncontrolled fire" can be either a fire that occurs on a floor where the sprinkler protection is shutdown or a fire that involves a fuel array that produces a fire of such intensity that it overwhelms the sprinkler protection. The most important safeguards are those that avoid the development of such a fire by tightly controlling and monitoring any shut downs of sprinkler protection and providing special fire suppression or fire resistive enclosures for unusual fuel concentrations, such as track file or other concentrated storage of exposed combustible materials.

Should these safeguards fail and an uncontrolled fire occurs, the building fans can be used to control smoke spread through the buildings and keep the exit paths and other floors in the building clear. The procedure, however, will apply pressures to the stairwell door on the fire floor capable of preventing egress from that floor and should never be initiated until the floor of fire origin is clear of all occupants and the fire has broken out of at least one window. This approach is discussed in greater detail in Section 6.4.1.

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[1] For the purposes of this study, the term "Core Pressurization" refers to the condition where the core supply fan is on, the toilet exhaust fan is off, the peripheral and inside space supply fans are off, and the interior space return fans are on and set to full exhaust (purge). See Section 4.0

A similar but lesser potential for disaster exists if an uncontrolled fire were to occur in 4 WTC or 5 WTC. Here, the shorter egress time lessens the potential. A recommendation is included, however, to consider providing smoke control for the stairwells in these buildings using dedicated fans.

In the event of an uncontrolled fire in 5 WTC under adverse conditions where a wind blew directly into the building through windows broken out by the fire, smoke could be driven throughout the Concourse. A similar fire in 4 WTC could result in a lesser smoke migration into the southeast portions of the Concourse. In the remote event of such a fire, smoke could be held out of the Concourse using the Concourse and tower fans as discussed in this report.

As a result of the analyses conducted, the following conclusions are drawn:

1. **Sprinkler Protection**

   The analysis in this project along with those in the previous project, Smoke Management Evaluation Study of The World Trade Center Concourse and Plaza (Hughes, 1996) show that, with the several exceptions noted herein, the provision of sprinkler protection will allow only minor smoke migration from the space of fire origin. All of these analyses of sprinklered fires indicate that exit paths, stairs and elevators will remain sufficiently free of smoke to be safely used for building egress. In these cases, persons proximate to the fire may have to evacuate the space of fire involvement but can find safe refuge in the core area or on an adjacent floor.

2. **Stairwell Protection in Towers**

   As discussed in Section 6.5.1, the height of the towers and the tower stairwells precludes effective traditional stair pressurization of major portions of the stairs by air injection. The protection of the stairs from smoke intrusion can be accomplished, however, by core pressurization in the expected cases and by positive pressure ventilation in the unlikely event of an uncontrolled fire. See Section 6.4.

3. Core Pressurization Smoke Control In Towers

The vast majority of anticipated fires in the towers will be small and controlled by the sprinkler system. In these cases, setting the HVAC systems to the Core Pressurization configuration (See Figure 6) will contain the smoke in the area of fire origin, and prevent the spread of dangerous levels of smoke and contaminants into the core, the stairwells, and the elevator shafts.

4. Positive Pressure Ventilation of Towers

As noted in the analysis, it is possible to hypothesize a fire of major magnitude that could involve an entire floor in one of the Towers. Such fires have occurred in office buildings without sprinkler protection, but to date we are unaware of any that have occurred in a sprinkler protected office facility. A fire involving an entire floor was used in this study to assess the potential of developing smoke management systems capable of withstanding the most severe exposure.

In the unlikely event that an uncontrolled fire develops, it is possible to use the HVAC fans to provide smoke control for the tower buildings, once that fire breaks out windows. The approach involves positive pressure ventilation[2]. (See Figure 7) This approach as described in Section 6.4.1 is designed to keep both stairwells and elevators clear of smoke and toxic gases. The use of these fans under these conditions can result in pressures on the fire floor stairwell doors that would prevent any persons still on that floor from escaping. It should never be used until that floor is clear of occupants, and only under the direction of the fire officer in charge of the incident.

5. Stairwell Smoke Control, 4WTC

In 4 WTC it is possible to use air flow, either provided by dedicated fans or diverted into the stairwell from the building system, to pressurize the stairwells

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[2] For the purposes of this study, the term "Positive Pressure Ventilation" refers to the condition where all supply fans are on, all toilet exhausts are off, and the only return fans that are operating (on exhaust mode) are those serving the HVAC zone where the fire occurs.

sufficiently to exclude smoke from the severe winter fire condition described above. This can be accomplished while not over-pressurizing the stairs.

6. Stairwell Smoke Control, 5 WTC

In 5 WTC is possible to use air flow as in 4 WTC to pressurize the stairwells. However, the air flow needed to provide for pressurization with up to 3 doors open can over-pressurize the doors when all of the doors are closed. For such a system to work in 5 WTC, it will be necessary to provide a nearly instantaneous pressure control device, such as barometric dampers. This is necessary to assure sufficient pressure when doors are open and prevent over pressurization when all doors are closed.

7. Smoke Control for Elevators, 4 WTC and 5 WTC

In both 4 WTC and 5 WTC there are vestibules outside the entrances to the freight elevators on each of the office floors. Simulations using air flow to pressurize these vestibules indicated that it is feasible to use air injection into these spaces to provide "areas or refuge" for handicapped individuals to be removed from the building via these elevators. In 5 WTC, the model indicates that it is necessary to inject 4,000 cfm into the vestibule on each floor. In 4 WTC, the model indicates that it is necessary to inject 3,000 cfm into the vestibule on each floor.

8. Smoke Flow Into Concourse

If the hypothesized severe winter fire occurs in 5 WTC, the analysis indicates that the smoke will spill out of that building into the Concourse and across the Concourse into the tower buildings. The analysis indicates that this flow can be restrained if one of the following options is employed:

a) The entire concourse and the towers are placed in a pressurization mode by shutting off the return and exhaust fans serving the Concourse and a sufficient number of return fans in the Towers to prevent flow from the Concourse into the Towers, or

b) Install doors that will be closed at the time of a fire to separate the Concourse and Plaza level entrances from 5 WTC to the Concourse, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8, or

c) Install doors that will be closed at the time of a fire on the escalator, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8.

Option (a) will confine the smoke to the floor of origin, keeping the exit routes clear throughout the fire. Options (b) and (c) will permit smoke migration into the lobbies on all floors below the fire floor, with some migration into the adjacent area of the Concourse, but the exit routes will remain clear.

9. Fire in PATH Terminal

A minor, sprinkler controlled, fire in the PATH terminal would result in local smoke and minor spread to those portions of the Concourse nearest the PATH entrance. In case of a major fire in the PATH terminal, without either sprinkler suppression or smoke control, smoke would spread widely over the entire Concourse and into the tower buildings. To prevent this it would be necessary for the entire Concourse to be placed in a pressurization mode, by shutting down return and exhaust fans serving the Concourse and adjusting the fans in the towers to prevent air flow from the Concourse into the towers. If this were done, however, the smoke from the fire would be forced into the PATH terminal and system.

10. Truck Fire at Loading Dock

If a fire develops in the cargo compartment of a large truck, shielded from the garage sprinkler protection, a serious condition of smoke migration into the adjacent tower can occur. With the combination of open loading dock doors and no smoke control in the tower, smoke can spread into the B-1 level. With the loading dock doors closed and the sub-grade levels and the lobby return fans off, smoke can be controlled, even on a severe winter day. The loading dock doors should be kept closed, or arranged to close automatically, in the event of a fire.

11. Tower Lobby Fire

The lobby HVAC system has the capabilities to be used as an atrium smoke control system to keep the exits through the lobby of a tower passable given a large (11,000 Btu/s) fire in the lobby. Under severe winter conditions it would be necessary to shut down sufficient supply fans in adjacent zones to prevent stack effect flows up the elevators from diverting smoke into the elevator shafts.

12. Passenger Car Fire In Garages

A fire involving a passenger car in the garage would not result in significant smoke migration into the adjacent buildings or obstruct egress from the garages.

13. Impact of Shutting Down Fans Upon Smoke Detection

Shutting down fans on smoke detection is less effective in terms of smoke control than leaving the fans on and spilling all of the return and setting the supply on 100% outside air.

14. Interrelationship of All Elements of WTC Complex

The analyses in this project re-enforce the fact that all of the HVAC systems in the entire complex interact significantly. Any major changes in one portion of the facility may impact other portions of the facility, potentially affecting the movement of smoke from a fire. The most significant impact is that produced by the PATH system on the Concourse and 5 WTC. Other impact could result if separate sections of the complex, such as one or more office building, were placed under separate HVAC management from the complex as an entity.

The report makes the following recommendations to the Port Authority, based on the analyses conducted and the conclusions drawn:

1. Sprinkler Protection (Entire Complex)

Complete the program for total automatic sprinkler protection of the entire complex. Where spaces are known to be used for storage or track files or other high concentrations of

potential fuel for a fire, provide extra protection in the form of additional suppression capabilities (i.e. increased discharge density from the sprinkler system), fire resistive enclosure of the space involved, or both.

2. Emergency Smoke Management Sequence in Tower Buildings

The following sequence of actions is recommended in case of a fire in one of the towers.

a) Notify the NY City Fire Department and follow the WTC emergency procedures for the floor involved and adjacent floors.

b) Upon activation of any smoke detector or sprinkler system, set the HVAC system covering the entire zone where the fire is detected to core pressurization.

c) If smoke detectors involving 2 or more detectors on floors other than the fire floor occurs, evacuate all floors served by the MER serving the fire floor that are on the same side of the MER floor as the fire floor; that is all floors served by the same supply fans that serve the floor of fire involvement.

3. Handling An Uncontrolled Fire in A Tower

While an uncontrolled fire is an unlikely event, it is prudent to provide contingency plans for smoke protected egress and refuge in case of such an event occurs. Plans to institute positive pressure ventilation as described in Section 6.4.1 should be developed and coordinated with the New York City Fire Department and regularly rehearsed and tested. Implementation of positive pressure ventilation by its nature is a fire ground action and would be implemented under the direction of the fire officer in charge with advice and assistance from the WTC engineers.

4. Smoke Control for Stairs and Elevators, 4 WTC and 5 WTC

It is recommended that pressurized smoke control be considered for the stairs and the freight elevator vestibules in 4 WTC and 5 WTC. (i.e., a dedicated fan system injecting air at multiple points in the stairs and into the vestibules each floor.) As discussed in the

analysis, barometric relief or other pressure relief will be needed in the stairs for 5 WTC. The recommended operating sequence is to initiate the Stair and vestibule pressurization upon activation of more than one detection of smoke in the plenum space. To lessen the circulation of smoke through the HVAC ducts, the HVAC system should not be shut down but set to total outside air with no recirculation.

5. Additional Area of Refuge Design Elements, 4 WTC and 5 WTC

The pressurization of the freight elevator vestibules is intended to provide the basis for "areas of refuge" for handicapped persons. If the Port Authority elects to use these vestibules for this purpose it will be necessary to:

a) Equip all of the vestibule doors with door closers triggered by the activation of the smoke control system.

b) Provide the necessary signage and communications system to identify the spaces as areas of refuge and enable anyone in the areas of refuge to communicate their location and needs to the WTC emergency control location.

c) Recall the elevators serving the vestibules to the exit floor and place them in emergency service. The accessible egress paths usable by a mobility impaired person is via the elevators serving these vestibules exiting at the Concourse or B-2 levels. Both of these routes are potentially exposed to blockage by smoke, though the likelihood of both being blocked is improbable, as demonstrated by the analysis in this report. For this reason it will be necessary to know the condition of the egress routes before evacuating anyone using the elevators. Evacuation should then be controlled by an emergency operator who is aware of any smoke in the exit routes and can act accordingly.

6. Keeping Smoke Confined to 5 WTC

A special problem exists in case of a severe fire in 5 WTC. If, in event of fire, the smoke detectors indicate smoke in three or more smoke detection zones, it is possible that a fire

overtaxing the sprinkler system has occurred. In this case there is a danger of smoke spreading into the Concourse and tower buildings. To counter this, if such a warning occurs, all of the returns from the Concourse HVAC systems should be shut down. If such a fire occurs under winter conditions, return fans in the towers will also have to be shut down to keep smoke within the perimeter of 5 WTC. Other approaches to controlling the smoke from a fire in this building were modeled (See Section 6.4.2), but none exhibited the same level of safety in 5 WTC and the Concourse open to it.

7. PATH Terminal

The Port Authority needs to continue its studies of smoke management in the PATH terminal. A minor, sprinkler controlled fire in the terminal would not present a serious hazard. A major fire, typified by a PATH car fire could, however, expel smoke into the Concourse, migrating either into the towers or into 5 WTC. The smoke could be held back by shutting down all Concourse return fans and sufficient return fans in the towers so that air flow is from the tower lobbies into the Concourse. If this were done, however, the smoke would be forced into the terminal and the PATH system itself. We understand that Port Authority Engineering has completed a preliminary design for the PATH Terminal smoke management system that is compatible with the criteria, assumptions, and findings of this study.

8. Interrelationship of PATH Terminal and Complex

It is important, however, that no solution that involves the closure of the PATH terminal from the Concourse be considered without evaluation of the effect of that closure on smoke movement in the Concourse. The PATH terminal is a major source of air that avoids a winter condition where the towers could impose a negative force on 4 WTC and 5 WTC.

9. Loading Dock Smoke Control

Damage to the doors between the loading dock and the tower building should be repaired. The rolling steel doors should be equipped with smoke detectors, arranged to close these doors if they should be open and a fire occurs at the dock. Additionally, if two or more smoke detectors in the return air from the B-1 space are activated, the supply to the sub-

grade portions of the tower involved and the supply to the lobby of that tower should be shut down.

10. Tower Lobby Smoke Control

In case of fire in the lobby of one of the towers, the lobby supply and return should be continued in operation with no recirculation and 100% fresh air supply and 100% exhaust of the return. In winter conditions the core returns for floors 1 to 6 and sub-grade areas should be shut down. Additional returns should be shut down until any flow from the concourse or outside into the lobby is mitigated. To implement this it is recommended that a pressure sensors be installed in each of the tower lobbies that measure the pressure difference between the lobby and the Concourse and between the lobby and the exterior. The data from these reading should be shown in the control room.

11. Further Tests

Tests of the proposed procedures should be conducted under both summer and winter extreme conditions prior to implementation of this study to verify the pressures predicted by the model. The procedures recommended above are based on calculations using the model CONTAM96. As such they involve the use of selected field measurements and assumptions relative to specific leakage paths and dimensions. It is felt that pressure differentials and pressures applied to doors in the means of egress are the key measurements. The use of smoke tracers, while not considered essential, could be of assistance in discovering unanticipated leakage paths.

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1.0 Introduction

This is a report on the Smoke Management Evaluation Study of the World Trade Center Complex, excluding the concourse and plaza levels, which were studied under an earlier report (Hughes, 1996). The report is divided into the following Sections:

1. Introduction
2. Tenability
3. Fire Scenarios
4. Smoke Control Modes
5. CONTAM 96 Network Model
6. Studies Based on Smoke Control Cases
7. Conclusions
8. Recommendations
9. References
10. Appendices

    Appendix A: CONTAM 96 Theory and Validation

    Appendix B: World Trade Center CONTAM 96 Models

    Appendix C: Interim Report

    Appendix D: Wind Pressure Profiles.

    Appendix E. Simulations

The World Trade Center complex considered in this study contains two 110 story towers (1 and 2 WTC), two 9 story buildings (5 WTC and 4 WTC), and interconnecting basements and concourse. The Concourse and a proposed enclosed Plaza were considered during the earlier study (Hughes, 1996), and were included in this evaluation only to the extent that they were important to the studies being conducted. The boundary conditions at the PATH terminal, the NYC Subway entrances, the Hotel, and the Customs House developed during the earlier study (Hughes, 1996) were included in the models constructed for this study.

The evaluation of the smoke management system and the development of alternative proposals was undertaken as an engineering analysis based on the physics of fire, smoke development, automatic sprinkler response, and smoke flow. Various engineering equations and models were used as described in Section 2 of this report. Major use was made of the mass movement network model CONTAM 96. The model, its validation, and its use in this project are discussed in Section 2 and documented in the several report appendices.

1.1 Smoke Hazard Potential

This analysis is based on fire safety conditions as they will exist once the program to provide sprinkler protection throughout the entire complex is completed. The provision of sprinkler protection is an ongoing program, currently tied to space renovation and is reportedly between 80 and 90 percent complete in the office buildings.

The current plenum smoke detectors are being replaced with a system of addressable smoke detectors. This will reduce the potential of false alarm and increase the ability to trace the movement of smoke from a fire.

For virtually all fire situations the sprinkler system will control the fire and the smoke can be confined to the space of origin by switching the HVAC system to "Core Pressurization"[3]

The exception of concern is the extremely unlikely but still remotely possible involvement of an entire floor or major portion of a floor in a fully involved fire. The fire used to model this condition is referred to in this report as an "Uncontrolled Fire." Such fires have occurred in other office buildings, and is discussed in greater detail in Section 3.3.2. If such a fire were to occur on any office floor in one of the towers and special smoke control measures were not taken, the results could be disastrous to those in the building involved, spreading potentially

[3] For the purposes of this study, the term "Core Pressurization" refers to the condition where the core supply fan is on, the toilet exhaust fan is off, the peripheral and inside space supply fans are off, and the interior space return fans are on and set to full exhaust (purge). See Section 4.0

lethal smoke through the building faster than the buildings can be evacuated. The potential is most severe in the tower buildings because of the long time required to exit these buildings. (See Section 6.12.)

The source of such an "uncontrolled fire" can be either a fire that occurs on a floor where the sprinkler protection is shutdown or a fire that involves a fuel array that produces a fire of such intensity that it overwhelms the sprinkler protection. The most important safeguards are those that avoid the development of such a fire by tightly controlling and monitoring any shut downs of sprinkler protection and providing special fire suppression or fire resistive enclosures for unusual fuel concentrations, such as track file or other concentrated storage of exposed combustible materials.

Should these safeguards fail and an uncontrolled fire occur, the building fans can be used to obstruct smoke spread through the buildings and keep the exit paths and other floors in the building clear. The procedure, however, will apply pressures to the stairwell door on the fire floor capable of preventing egress from that floor and should never be initiated until the floor of fire origin is clear of all occupants and the fire has broken out of at least one window. This approach is discussed in greater detail in Section 6.4.1.

A similar but lesser potential for disaster exists if an uncontrolled fire were to occur in 4 WTC or 5 WTC. Here, the shorter egress time lessens the potential. A recommendation is included, however, to consider providing smoke control for the stairwells in these buildings using dedicated fans.

In the event of an uncontrolled fire in 5 WTC under adverse conditions where a wind blew directly into the building through windows broken out by the fire, smoke could be driven throughout the Concourse. A similar fire in 4 WTC could result in a lesser smoke migration into the southeast portions of the Concourse. In the remote event of such a fire smoke could be held out of the Concourse using the Concourse and tower fans as discussed in this report.

2.0 Tenability

2.1 General

The design criteria used in this study are based on a determination of the distribution and extent of conditions that would cause harm to persons in the spaces, or which would obstruct evacuation. The principal tool used for this analysis was the network model CONTAM 96. This model is discussed in detail later in this report. In addition, analysis was made of the vision distance and CO contamination. It was assumed that conditions would be unacceptable if the vision distance was less than 200 ft., or if the CO concentration would result in a carboxyhemoglobin (COHb) level exceeding 12% in exposed individuals during the course of the fire.

Representative design fires were developed using existing test data and experience. Door opening forces were considered to be excessive if the opening force exceeded 30 lbs. (See Section 6.7 for the calculation method used.)

2.2 Environmental Conditions

For the CONTAM 96 simulation, it was assumed that the internal temperature in the complex was 70°F. For the cases involving an uncontrolled fire (Section 3.3.2), it was assumed that the temperature in the space of fire involvement was 2,000°F. Exterior conditions were varied. In most cases either a severe (windy) winter day or a still summer day were simulated.

Winter conditions were simulated as an outside temperature of 15°F and a westerly wind with wind speed varied with height above grade. The wind speed is profiled in Appendix D.

The conditions simulated varied from approximately 10 mph at grade to 60 mph across the top of the 110 story towers. Summer conditions were simulated at an outside temperature of 90°F and no wind.

To study the impact of wind versus temperature, a few cases were run with the outside temperature set at 15°F with no wind and with outside temperature set at 70°F with the same westerly wind as simulated for winter conditions.

2.3 Vision Distance

Vision distance was calculated using the vision mass product density relationships reported in FPETOOL (Nelson, 1990). The equation used is:

$$V_e = \frac{3}{e_s M_p} \qquad \text{Equation 1}$$

where:

V_e = Distance in meters at which there is approximately a 95% reduction in light transmission. (At this level of light an illuminated exit sign can be seen.),

e_s = Specific extinction coefficient. (m^2/g) A value of 0.1 m^2/g was used for the office, uncontrolled (total floor burn out), truck, and kiosk fires in this analysis. This is a reasonable representation of the smoke obscuring properties of a free burning mix of common materials as found in these areas. A value of 0.5 m^2/g was used for the car fire due to the high concentration of polymers which produce smoke with distinctly different obscuration properties. (Tewerson, 1988, and Mulholland, 1995)

M_p = Mass of fuel burned per unit volume as a concentration in the space under evaluation.

2.4 CO Exposure

Exposure to CO was modeled as carboxyhemoglobin (COHb) uptake based on Stewart's equation as reported by Purser (1995).

The equation used is:

$$\%COHb = (3.317 \times 10^{-5})(ppm.CO)^{1.036}(RMV)(t) \quad \text{Equation 2}$$

where:

%COHb = The percent carboxyhemoglobin accumulated in the blood stream of a person exposed to the indicated Level of CO for time *t*.

ppm CO = CO concentration in parts per million

RMV = Volume of air breathed (L/min)

t = exposure time (min)

A base value of 18 L/min was assumed for the RMV, since it is a typical breathing rate for an active person. This can be as much as twice the rate for a person at rest (e.g., typical resting respiration rate is 9 L/min) and half the rate for a person under heavy physical stress (e.g., 36 L/min).

The % COHb is a measurement of the extent that carboxyhemoglobin has replaced oxyhemoglobin in the blood, and is the basis of harm from CO exposure. In general, a normal adult will be incapacitated if the COHb level approaches 30%, and may die if it approaches 50%. Given that an individual's susceptibility is very dependent on their physical condition, and that it has been demonstrated that negative effects on human psychomotor performance do not begin to occur until COHb levels exceed 12%, the tenability criteria for this study was set at 12% COHb. (Purser, 1995)

3.0 Fire Scenarios

The development of representative fire scenarios involves development of design fires, the design fire location within the complex, seasonal weather variations, HVAC system variations, building variations, and candidate smoke control variations. Table 3.1 provides a summary of

the fire scenarios used in this study. The investigation involved numerous permutations of these to analyze the potential fire scenarios and candidate smoke control systems.

1. In the tower, the fire locations were selected based on the HVAC system layout. Floors were chosen in both the upper and lower sections of HVAC zones to evaluate the effectiveness of the control strategies. Floors at low, mid, and high elevations were chosen to evaluate the impact of stack and wind effects.

2. Since concise data on the presence of open interior stairs (tenant stairs) are not available, some simulations were run where the stairs are located in floor openings that breach the HVAC zones.

3. The impact of a work station fire in the tenant space on the upper sky lobby, Floor 78, was assessed. The sky lobby floors observed during the site visit are extensively subdivided into tenant various tenant spaces, which make an effective barrier to fire spread. The uncontrolled fire involving the entire floor was not considered a potential on this floor.

Table 3.1 Summary of Fire Scenarios

Building	Fire Scenarios
WTC Towers 1 and 2	office workstation, uncontrolled fire, car in garage, truck at loading dock, kiosk in atrium, and kiosk in concourse.
WTC 4 and 5	office workstation, uncontrolled fire, and truck at loading dock.
Path Terminal	kiosk at newsstand level, and a 20MW fire used for a *trace contaminant source*
Sub-grade Levels	car in garage, and truck at loading dock

3.1 Discussion

Based on tours of the complex and experience, five design fires were selected that represent conservative but reasonable estimates of fires that may occur in the World Trade Center complex: an office workstation, an uncontrolled fire, an automobile, a truck, and a kiosk. Each of these are discussed in greater detail below.

3.2 Assumptions

For all cases where the HVAC fans are operating, it is assumed that the electrical power supply to the fans continues to be available throughout the fire.

Unless specified otherwise each of the scenarios incorporated the following assumptions about the sprinkler protection:

1. The entire fire area is protected by an automatic sprinkler system.
2. The sprinklers are standard heads rated at 165°F,
3. The initial flow out of the first heads operating will be 0.2 gpm/ft^2, and
4. The sprinkler design criteria is 0.10 gpm/ft^2 over the most remote 1,500 ft^2 in office areas, and 0.16 gpm/ft^2 in storage and below grade areas.

For each of the scenarios, it is assumed that the fire is not detected until the first sprinkler or plenum smoke detector activates. It is expected that the sprinkler system will not extinguish all of the fires. For those fires that will not be extinguished by the sprinkler system, the fire's life (i.e., the time during which smoke continues to be produced) was determined by estimating the alarm transmittal and fire department response time.

In estimating these times, it was assumed that the water flow or smoke detection alarm is transmitted to the fire department within 3 minutes, and that the fire department alarm and response time will average an additional 10 min. from receipt of the alarm to arrival at the site.

Allowing 10 min. for the fire department to arrive on the fire floor, locate the seat of the remaining small fire, and to extinguish that fire, a total of 23 minutes have elapsed from initial alarm to extinguishment. This time will be added to the time to first sprinkler activation, which is described under each scenario, to arrive at the total time of fire life for each case. The uncontrolled fire was modeled as though the fire department was unable to control it until the fire essentially burned itself out.

3.3 Fire Scenarios

3.3.1 Work Station

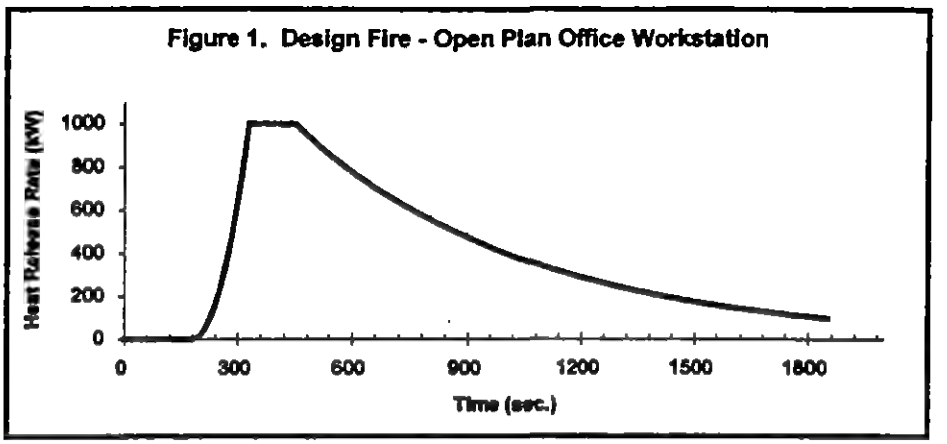
Recent work by at NIST (Madrzykowski 1992) and at the National Research Council - Canada (Lougheed 1996) has assessed the fire potential of open plan office workstations. Full scale fire tests were conducted in both efforts.

While there are differences between the data reported, they are not substantial, and appear to be largely due to differences in the workstations tested and the fuels placed under the horizontal surfaces of the stations. Combustible fuels located under these surfaces will be shielded from the water spray from a sprinkler. Since the sprinkler may not be able to extinguish these fires, they are assumed to continue to burn, at a reduced rate, until manually extinguished.

The design fire curve to be used is that proposed by Lougheed (1996). This curve was generated by plotting the results of seven full scale tests and drawing a curve that encompasses all seven of the test curves, overestimating each of the individual tests. This provides a conservative estimate for the design fire. Figure 1 shows the heat release rate curve of the workstation fire that was used in this study.

The curve proposed by Lougheed represents a more severe fire than is indicated by the Madrzykowski work due to differences in the design of the workstations tested, and due to the heavy fuel loading placed in the concealed areas under the desks and tables. Lougheed's tests

were conducted on workstations that appear to be similar to the most severe cases observed in the World Trade Center complex during site visits and surveys.



Given the selection of this design curve, the next question is to determine the point on the curve at which the fire is extinguished, and smoke production ceases. In Lougheed's seven tests, the first sprinkler activated at between 3:46 min. and 5:40 min. after ignition. For this analysis a conservative estimate of 6:00 min. for time to activation of the first sprinkler is adopted. Adding this to the 23 minutes from initial alarm to extinguishment (See *Assumptions*, Section 3.2) yields a fire life time of 29 min. A 30 minute burn time was used in this analysis.

3.3.2 Uncontrolled Fire

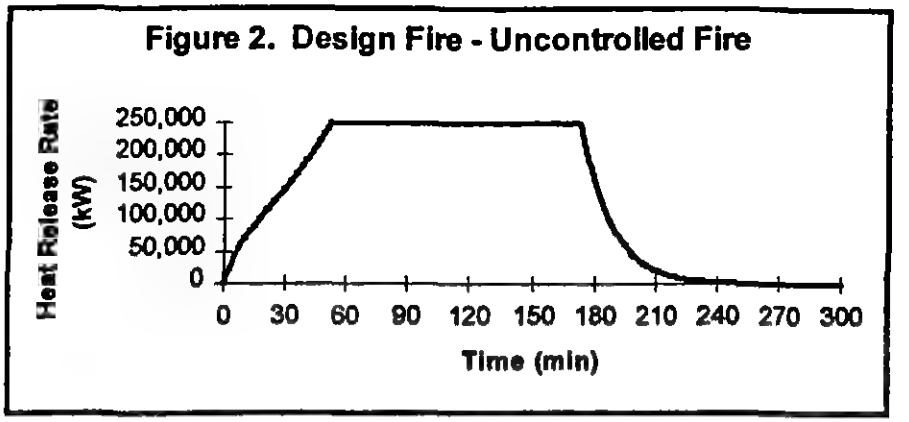
There is a potential of a fuel load in on office area that exceeds the capacity of the sprinkler system. Testing by Lougheed, et. al. demonstrates that mobile shelving units can overtax standard light hazard sprinkler system designs (Lougheed, 1994). While modifications to the sprinkler design and flow rates can help to alleviate this problem, it is reasonable to expect that similar conditions may exist somewhere in the complex.

Mobile shelving units represent one of the most challenging office occupancy fuel packages from a fire suppression point of view since much of the fuel load is located under metal shelves that are packed tightly together. The heavy concentration of combustible materials and the shielded configuration combine to create a situation where the typical "Light Hazard" sprinkler system design that is the standard design in the complex can be inadequate to suppress, or even to contain, the fire. This is a realistic scenario to model the case where the sprinkler system is overtaxed by the fire, or for when a sprinkler system is turned off for any reason. Nearly any other collection of high piled combustible storage should produce the same results—a total floor burned out.

This fire was modeled after those that occurred at the First Interstate Bank in Los Angeles (Nelson, 1989), and the 1 Meridian Place fire in Philadelphia. (Klem, 1991) In each of these fires, a localized fire grew to flashover and spread to adjoining spaces on the floor. These in turn grew to flash over, and spread the fire farther along the floor. This sequential spread continued until the entire floor was fully involved, a process that took 30 minutes to an hour. During that time, most of the windows broke out and the fire also spread to floors above via interior and exterior routes.

A fire spreading beyond the sprinkler design area, or one which exceeds the capability of the system to suppress will open more and more sprinklers, resulting in a significant decrease in the quantity of water discharged from each head, to the point where the sprinklers are completely ineffective. It is assumed that the fire will not spread vertically to the floor above, since sprinklers operating on the floor above such serious fires have been shown to prevent this type of fire spread. (Klem, 1991)

A uniform fuel loading of 12 lbs/ft^2 (Caro, 1995) is assumed, for a total of 360,000 lbs on the floor. Also assumed is an average heat of combustion of 15 kJ/kg. The design fire shown in Figure 2 was used, based on analysis of previous fires of this magnitude. (Nelson, 1989) This fire grows to 60,000 kW in 7.5 minutes, and then increases every 15 minutes by 60,000 kW, simulating involvement and flashover of additional floor areas. After reaching 250,000 kW, the fire burns at that rate for 2 hours, and then decays for 2 more hours. The total mass loss under this design curve is 160,000 kg (352,000 lb).



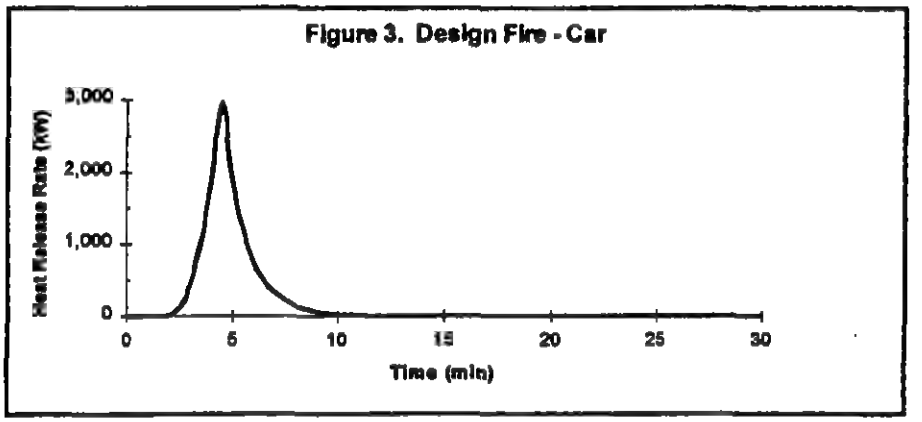
3.3.3 Automobile

Fire tests on automobiles have been conducted by a number of researchers. Due to variances in the test protocols and data recorded in each of the efforts, there is considerable divergence between the results reported. This appears explainable by the differences in instrumentation, vehicles tested, and the ignition scenarios used.

Mangs (1994) and Shipp (1995) reported heat release rate (HRR) from their tests, which were conducted without automatic sprinkler coverage. Mangs' tests produced peak HRR ranging from 1.5 to 1.9 MW, while Shipp reported HRR of 4.3 and 8.7 MW. Australian tests (BHP, 1987) did not report HRR, but instead reported air and structural element temperatures above and around the fire. The BHP work clearly illustrates the effectiveness of automatic sprinklers in controlling vehicle fires. The ECCS produced an extensive review of the work by Mangs and BHP (ECCS, 1993), although it focuses on the unsprinklered work by Mangs, and draws conclusions based on an unsprinklered parking garage.

This scenario assumes that the sprinklers are present and operable, and the design fire is based on this assumption. The design curve shown in Figure 3 shows the heat release rate curve for this scenario. This curve was generated by plotting the three vehicle fires reported by Mangs and the two fires reported by Shipp together and generating a "design" fire curve that encompasses all of the five fires. This curve was then input into the Detact model found in FPETOOL (Nelson,

1990) and was used to estimate the sprinkler activation time of 276 seconds, based on a ceiling height of 10 ft and 10 ft, by 10 ft spacing of sprinkler heads. It is assumed that the fire growth stops at sprinkler operation, and that the fire begins to decay at that time, as was show by BHP (1987). The peak heat release rate was determined from the unsprinklered "design" fire curve at the calculated sprinkler activation time.



The decay portion of the curve was developed by estimating the mass lost in garage vehicle fires under operating sprinkler systems, as reported by BHP (1987). This report provided estimates of the quantity of interior fuels unburned following extinguishment, which ranged from 30% to 50% of the total. The EC report estimates the energy content in the heat release rate curve for each of the four major fuel packages in a vehicle: the passenger cabin, the engine and front tires, the trunk and rear tires, and the fuel. The passenger cabin contains the largest fuel package in a car, reported as 47%, or 1.89GJ. Assuming an average heat of combustion of the materials in an ordinary car is 15MJ/kg (7,000 Btu/lb), the estimated mass of combustibles present is 47 kg (104 lb). Taking a conservative estimate of 50% of this fuel is unburned, based on BHP, gives an estimate of 23.5 kg (52 lb) of material will be burned in the design fire. The mass loss was estimated as a function of the heat release rate, and a decay curve was constructed so that the area under the corresponding mass loss curve resulted in a total of 23.5 kg mass loss. The time of decay was based on analysis of the air temperature data reported by BHP.

A comparison of this curve against those reported by BHP, which reported only air temperature, and not rate of heat release, shows a general correlation. BHP reported on four test fires conducted under automatic sprinklers. In each case the fire was easily controlled, with the

sprinklers operating at between 37 sec and 4:10 after ignition. The sprinklers cooled the fires quickly, as shown by the rapid reported temperature decreases.

In this case, as in prior scenarios, burning time was used to estimate the quantity of smoke, CO and CO_2 released during the fire. A 30 minute simulation time for the auto fire was used.

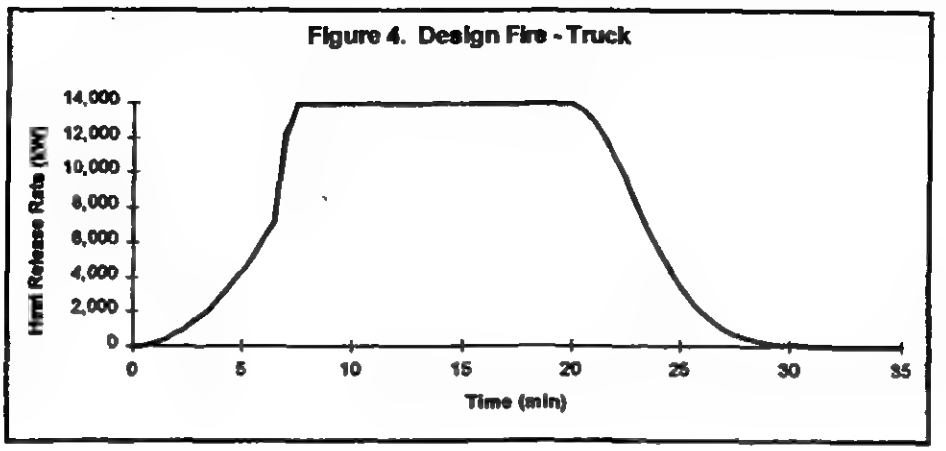
3.3.4 Truck Fire

This fire was selected since it represents a severe smoke generation condition. A fire inside a truck at a loading dock will be shielded from the sprinkler system until the truck body collapses, so the sprinkler system will be largely ineffective in controlling smoke production. A fire in truck would be ventilation limited, and thus produce large quantities of unburned soot and CO. Since the fire would be shielded from the sprinkler, it will continue to burn until the fire department effects manual suppression. It was assumed that the plume extending out of the open door will activate the sprinklers, which would cool the roof of the truck, delaying collapse. It was further assumed that the sprinkler operation will affect the combustion chemistry in the plume, and that continuing combustion in the region of the plume will be severely constrained by the cooling effects of the sprinkler operation. As a result of this effect, it was assumed that the CO production rate of this fire is ten times that of the other design fires in this study (Nelson, 1989).

The model FIRE SIMULATOR from the FPETOOL (Nelson, 1990) collection was used to estimate the initial and maximum growth rate. It was assumed that the initial fire developed as a fast t-squared fire (i.e., 0.044 times the square of the elapsed time in seconds) until flashover inside the cargo compartment. At that point, the maximum rate of heat release was controlled by the amount of air available through the open doors of the cargo compartment (i.e., assumed to be 8.5 ft high and 11 ft wide). FIRE SIMULATOR indicated a rate of heat release of about 13,000 kW, which was rounded up to 14,000 kW for this analysis.

The design curve shown in Figure 4 shows a fast developing fire inside a truck that has a lining of 1/2 inch plywood on the interior walls and top. The fuel load inside the truck is estimated at

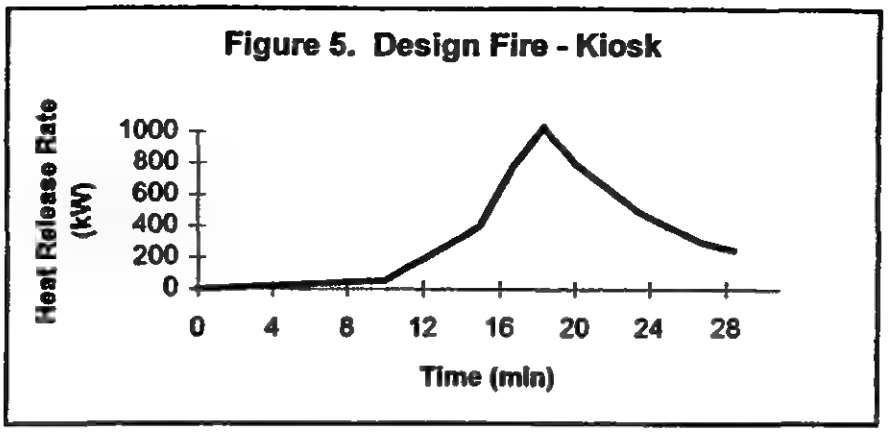
50 lbs/ft^2. The curve assumes fire department operation starts at 20 minutes, and total extinguishment 15 minutes later.



3.3.5 Kiosk Fire

The National Institute of Standards and Technology (NIST) has recently conducted tests of kiosks that are similar to the push carts used in the concourse and the commercial displays observed on the Mezzanine Level of the towers. The kiosks tested were slightly less than 4 ft by 4 ft in plan and 6 ft 9 in tall. The kiosks were loaded with hanging tee shirts in the upper display area and tee shirts in cartons in the cabinet space under the sales area. The burning rates of the kiosks tested are reasonable similar to the burning rates expected from the push carts and displays observed in the World Trade Center during the site visit. Figure 5 shows a plot of the average heat release rate from several kiosk tests.

This scenario was used in the prior study on the Concourse and Plaza levels of the complex. The fire model, the sprinkler model, and the CO and CO_2 generation models used in the previous study (Hughes, 1996) were used in this study.



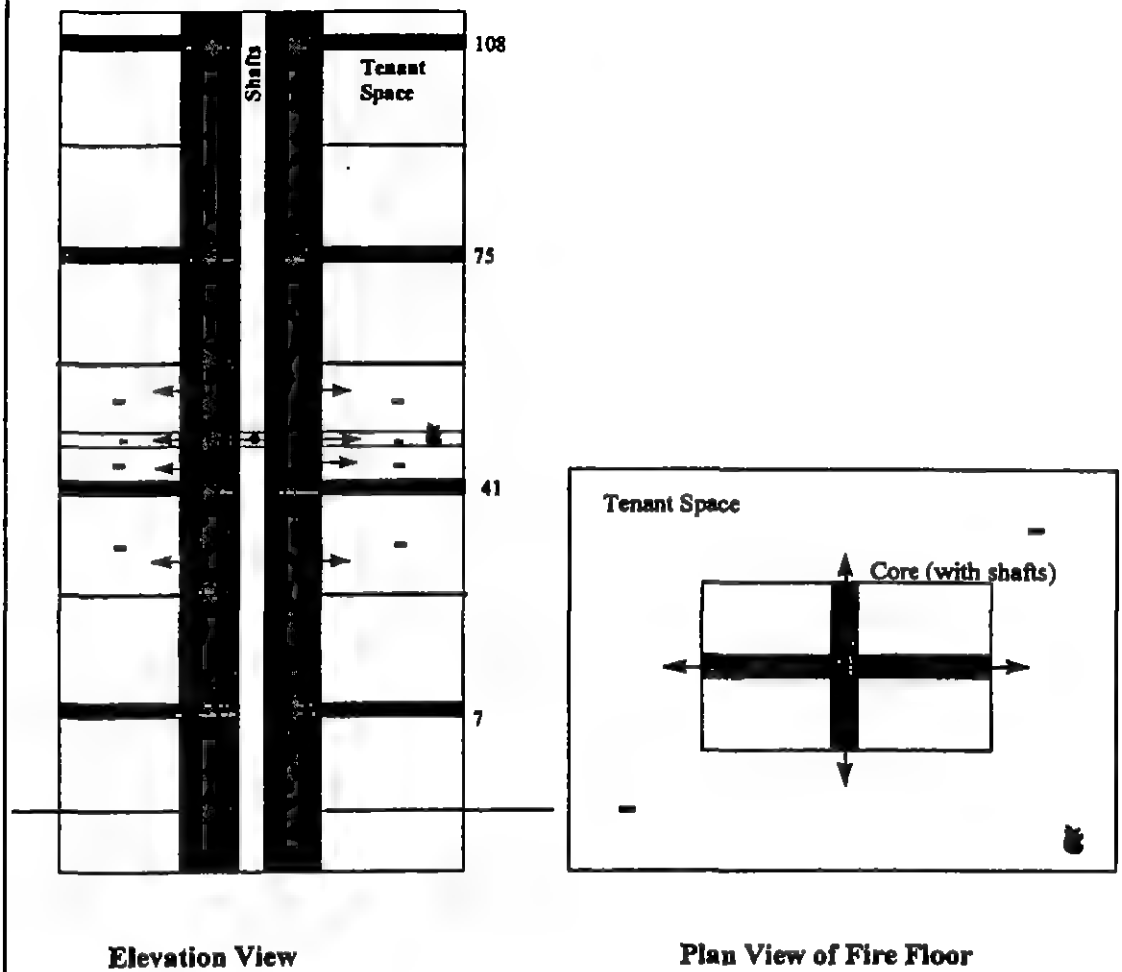
4.0 Smoke Control Modes

The study considered several conceptual smoke control designs, as well as simulations where no attempt at smoke control was made. Smoke control options were principally chosen from the currently available HVAC control selections, although simulations were made using concepts that would require modification to the existing HVAC systems.

For the purposes of this study, an HVAC zone in the towers is defined as those floors which are served by a given set of supply air fans, including peripheral air supply, inside space supply, and core supply.

One existing method of smoke management in the tower buildings is commonly called "Core Pressurization." For the purposes of this study, the term "Core Pressurization" is defined as the condition where the core supply fans are on, the toilet exhaust fans are off, the peripheral and inside space supply fans are off, and the inside space return fans are on and set to full exhaust. (See Figure 6)

Figure 6. Core Pressurization Smoke Control Mode



5.0 CONTAM 96 Network Model

The network model CONTAM 96 (Walton, 1996) was used to analyze the movement of smoke in the complex.

Appendix B catalogs the physical dimensions, the geographical relationship of the spaces, the openings and other flow paths, the HVAC and smoke exhaust capacities and other data used in the CONTAM 96 modeling of the World Trade Center Complex and Towers.

The CONTAM 96 model is a interactive network model designed for analyzing the air movement and air quality in multi-zone buildings. The equations are derived from Bernoulli's equation for air flow and conservation equations for the spread of contaminants. The equations as reported by Walton are included in Appendix A. In addition, Appendix A provides information on the procedures used to validate the model.

An attempt was made to build a single model of the entire World Trade Center complex within CONTAM 96. The large size and complexity of the complex exceeded the capacity of the CONTAM 96 model within the constraints of this study. Two separate models were constructed: The first was a model of one of the towers, and the second was a simplified model of the complex, wherein the effects of the towers, the PATH terminal, the subway entrances, the Customs House, and the Hotel were estimated as in the previous study. (Hughes, 1996) The tower model included more than 3,200 zones and 14,000 flow elements, and the complex model had more than 470 zones and 1,470 flow paths.

To build the models, the complex was divided into zones comprised of spaces, rooms, atria, and other describable features. Appendix B contains diagrammatic sketches produced by CONTAM 96 detailing the arrangement of the WTC complex as used in this study.

Airflow sources (fans or entire HVAC systems) were modeled as simple air handling systems. A system is defined, and supply and return points are added to the appropriate zones according to the fan schedules developed, and described in Appendix B.

The contaminant produced by the fire was simulated as a mass in the zone of fire origin. The contaminant source term was entered as a time dependent variable following the data for mass loss rates derived from the heat release rate curves shown in Figures 1 through 5. The model cannot locate the fire to any specific point in the zone and, therefore, it is assumed that the mass produced by the fire is well mixed within that zone. This assumption is reasonable, though the

model cannot consider a case of a fire located directly in front of an opening between two zones; for example, the escalator openings into 5 WTC.

Test measurements were taken during a visit to the site on June 28 - July 2, 1996. These were used to calibrate the initial conditions represented by the building as it stands at this time. The field measurements, procedures used, and data collected were reported in an interim report to the Port Authority, which is included herein as Appendix C. The wind pressure impact on the these buildings was also included in the model. (See Appendix D)

Upon completion of the Tower model, a series of simulations were conducted to calibrate the model. The simulations, illustrated in Cases nel-1 through nel-5 in Appendix E, were designed to replicate the physical conditions observed and measured during the site survey.

As anticipated, the simulations showed some disagreement between the simulation results and the measurements taken during the site survey. The principal difference was in the stair and elevator shaft pressures. Some difference was expected since the model was based on all doors being closed, and during the testing, an uncertain number of doors were open.

In order to fine tune the model, the leakage path areas for stair doors, passenger elevators, and selected other doors were increased. This distributed the leakage from the open doors throughout the full height of each shaft, a desirable approximation since it is reasonable to expect under the current building management systems that some doors will always be open, and that it is impossible to predict which doors these will be. The corrected leakage path areas are shown in Table B-2. Following these adjustments, the simulations gave results that are in reasonable agreement with the measurements obtained during the testing.

CONTAM 96 produces a massive amount of detailed data that can be difficult to present in a useful manner. To overcome this, the post processing procedure developed during the earlier study was adapted further, and used to evaluate the life safety factors in each of the subdivisions (CONTAM 96 zones) in the model. Using the vision distance and COHb equations, the data were converted to estimates of the vision distance, CO concentration, and carboxyhemoglobin concentrations expected due to exposure to the fire produced environment.

For analysis purposes these results were sorted to report all zones where the vision distance was less than 200 ft. The data were then mapped on floor plan sketches of the Concourse, Plaza and Mezzanine. The shaded areas in the sketches show those zones where the vision distance was less than 200 ft. Appendix E shows the output data produced and selected sketches that are referenced in this report.

More than 200 different cases were evaluated during the study. Each was designed to evaluate the effects of changes to selected variables on the spread of smoke within the areas modeled. Several general groupings of cases were conducted, and are reported as:

1. Model calibration cases,
2. Tower studies: Total Floor burn-out cases,
3. Tower studies: Work Station fire cases,
4. Tower studies: Pressurization cases,
5. Tower studies: Tracer fire cases,
6. Tower studies: Fire detection system interaction cases,
7. Tower studies: Truck fire at loading dock cases,
8. Tower studies: Automobile fire in garage cases,
9. Complex studies,
10. Stairwell pressurization studies: Tower,
11. Stairwell pressurization studies: 4 & 5 WTC,
12. Elevator vestibule pressurization studies, and
13. PATH terminal fire studies.

Two important variables, weather and stair doors, were also considered during the simulations.

The impact of two extreme weather conditions on the performance of the smoke control system was evaluated. The extreme winter condition (to maximize the impact of the stack effect) was simulated as 15°F outside temperature with a wind varying from 10 mph at street level to 60 mph blowing across the top of the towers. Using the wind pressure profile described in Appendix D, the pressure created by this wind at each level and each face of the building was modeled. The

extreme summer condition (to maximize the impact of the reverse stack effect) was simulated as 90°F outside temperature with no wind blowing.

The impact of open and/or closed stair doors on the movement of smoke and the force required to open other closed doors in the stairwell was evaluated. In the Towers, the worst case for smoke control was modeled as all stair doors opened, except those stair doors on the fire floor, to simulate the effect of a simultaneous total egress from the building. Similarly, the worst case for door opening force was modeled as all stair doors closed, to simulate the impact of the smoke control system being placed in operation before egress begins. In 4 WTC and 5 WTC, the worst case for smoke control was also modeled as stair doors open, simulating egress of the fire door and the adjacent floor, and door opening force was based on all doors closed at the initiation of smoke control.

6.0 Studies Based on Smoke Control Cases

The separate cases were evaluated using CONTAM 96 models of the buildings and complex. Results of selected individual case studies are shown Appendix E. The cases were run to simulate the various potential fire exposure conditions and methodologies for smoke management. Discussion of the approaches and results are grouped by potential fire problem area below.

6.1 Fire Involving an Office Work Station in Sprinkler Protected Space.

It is the plan of the Port Authority to protect the entire World Trade Center Complex with automatic sprinkler protection. At present approximately 80 to 90 percent of the spaces in the office buildings are so protected. In accordance with the instructions of the Port Authority, all of the cases in this analysis are based on total sprinkler protection.

As discussed in Section 3.3.1, the rate of heat release curve developed by the National Research Council - Canada (Lougheed 1996) as shown in Figure 1 was used to represent the maximum

rate of heat release and mass loss to be expected under office type sprinkler protection. This type of fire represents the worst case for the vast majority of the potential incidents in office space.

Cases LAM-9, LAM-10, NEL-7, NEL-12, NEL-41, NELS-63, NELS-63A, NELS-66, NELS-67, NELS-68, NELS-70, and NELS-71 all used the fire curve from Figure 1 as the source for heat and contaminant production. In each case the contaminant was located in the general office space. In every case smoke contamination was confined to the zone of fire origin or immediately adjacent zones and no life threatening conditions occurred beyond these zones. This limited spread of contamination occurred whether or not any smoke control measures were simulated. These cases demonstrate the ability of the Core Pressurization mode to confine the smoke from a small fire to the zone of origin.

As long as the sprinkler protection is present and in service and no extraordinary fire that overwhelms the sprinkler protection occurs (See Section 6.4 for discussion of such cases), the models show that there will be no smoke migration into exit routes or remote areas and no development of harmful conditions away from the immediate area of fire involvement.

6.2 Fire in Lobby of One or Two World Trade Center.

The lobby area in each of the towers has an air supply of approximately 180,000 cfm with the supply entering the lobby at or below the 2nd Floor slab. Approximately 170,000 cfm exhaust is provided with exhaust intakes near the top of the 6 story lobby. If these supplies and exhausts are kept operational at the time of fire and the exhaust is discharged without recirculation, smoke management for a fire within this atrium space can be achieved.

This analysis is based on the assumption that all areas under balconies will be sprinkler protected, in which case the conditions described in Section 6.1 apply for any fires initiating in the space under a balcony.

The case of concern here is a fire occurring under the open space between the Plaza Level balcony and the building core or on the Plaza Level balcony. The ability to maintain the smoke

level interface at a given position is described in NFPA 92B (NFPA, 1995) and expressed in terms of volume flow in the 1993 BOCA National Building Code. The BOCA form of the equation was used. It is expressed as:

$$V = 20.8 Q_c^{1/3} z^{5/3} + 3.98 Q_c \qquad \text{Equation 3}$$

where

V = volumetric rate of smoke inflow (rate of exhaust required) (cfm),

Q_c = convective fraction of the rate of heat release (Btu/s), and

z = height above the base of the source fire (ft).

In the above equation:

$$Q_c = f_c Q \qquad \text{Equation 4}$$

where

Q = total rate of heat release (Btu/s) and

f_c = convective fraction (taken as 0.7 in this report.)

The worst case fire in terms of the ability of the exhaust system is one with its base at the lobby (Concourse) floor level. Since the Plaza level (mezzanine) is not only open to the public but is also the level of exit discharge for two of the stairwells, it is important to keep smoke from a fire in the lobby high enough above the walking surface of the Plaza level to allow egress. The Plaza level slab is approximately 23 ft above the lobby slab. It is desirable to maintain the bottom of the smoke level from a fire at the lobby floor at least 7 to 10 ft above the Plaza level slab.

Using the exhaust flow rate of 170,000 cfm, and solving Equations 3 and 4 for the height above the Lobby slab (z) and total fire size (Q) indicates that the existing system can maintain the smoke layer from a fire of approximately 11,000 Btu/s at a level 33 ft above the Lobby slab (10 ft above the Plaza level slab). The equations also indicate that the smoke layer will be maintained 7 ft above the Plaza level slab even if the fire should be able to sustain a rate of heat release of 15,000 Btu/s. Any fires initiating on the Plaza level would have a lesser impact on smoke layer level for the same fire.

In the NIST Kiosk test (Mitler, 1996) the maximum rate of heat release experienced when the kiosk was allowed to burn itself out without sprinkler or other suppression action was 3000 Btu/s. Even in that case the peak 3000 Btu/s was sustained for only a brief period of time. Nelson and Forssell (1994) report the heat release rate of wood (pine) as between 12 and 24 Btu/s-ft^2 depending on the energy feed back from the exposing flame. The production of 11,000 Btu/s from wood or similar common cellulosic based materials (as might be used in a booth or display) would require the involvement of about 500 to 1,000 ft^2 of burning surface. For gasoline the rate of heat release is approximately 200 Btu/s-ft^2 (Babrauskas, 1995). A gasoline pool of approximately 55 ft^2 (8 ft diameter) with sufficient fuel depth to sustain that level of burning would also produce a sustained fire of 11,000 Btu/s. Both of these examples are expected to exceed any exposure fire likely to occur in the lobby.

The only openings from elevator shafts into the lobby are at the 1st Floor level. During business hours and during other than severe winter conditions, the stack effect impact in the lobby are modest and it is reasonable to expect that little if any of a rising plume from a fire might be diverted from the upper portions of the lobby into the elevator shafts. During severe winter cold, when the fans are at reduced settings, a strong inflow of air from either the exterior of the building or the Concourse into the lobby can be present. In such a case this inflow can divert the rising fire plume into the elevator shafts and transport at least a portion of the smoke to remote areas of the building. In the case of such a fire it is important to boost the pressure in the shafts to counter this in flow without shutting down lobby exhaust.

6.3 Truck Fire at the B-1 Level Loading Dock.

The principle loading dock for the complex is located at the B-1 Level adjacent to 1 WTC and 2 WTC. Delivery vehicles of all sizes use this facility. Some of the vehicles are full size, over the road tractor-trailer combinations. As discussed in Section 3.3.4, evaluations were made of the impact of a fire within the cargo of such a large vehicle. The fire case is based on an incident involving a truck parked at the dock with its cargo doors open and a flashed-over fire within the trailer. As noted in Section 3.3.4, a fire of approximately 14,000 kW with high carbon monoxide production is possible and is used as the basis for the simulation. See cases NEL-8, NEL-9, NEL-14, NEL-15, NEL-16, NEL-19, NEL-27, NEL-28 and NEL-29.

The separation between the loading dock and the B-1 levels in each of the towers consists of two "air lock" doors and two rolling steel doors. The "air lock" doors are composed of a vestibule with a power operated sliding door at one end and a heavy rubber door at the other end. At the time of the visit to the site by the project team, one of the "air lock" doors in 2 WTC was defective in that the power door was open and inoperable, and the rubber door had a large gap between the door and its frame. The analysis in this report are based on the necessary repairs being made to these doors. The rolling steel doors open directly from the B-1 level to the loading dock. At the time of the site visit in August, 1996, one of these doors was open in each building. The various cases are based on the "air lock" doors always being in the closed position. Some cases address the situation with the rolling steel doors open, others with these doors closed.

Cases NEL-8 and NEL-9 simulate the conditions on a severe winter day with building systems in normal operation and no special smoke management efforts. Case NEL-8 simulates smoke spread with the rolling steel doors closed. Case NEL-9 simulates the situation with these doors open.

With no smoke control and the rolling doors closed, Case NEL-8, smoke migrates in the general area of Level B-1 at an approximately linear rate, reaching an obscuration level of 50 ft in 30 minutes. Smoke also spreads into Stair 3 but not into the basement stair, and into the several elevator shafts that serve the B-1 level. Vision distance in Stair 3 at the B-1 level drops at a linear rate over 30 minutes to a vision distance of approximately 100 ft. Smoke in Stair 3 also migrates at a lesser density to Level B-2 and B-3 of that stair. The area of the loading dock has severe decreases in vision distance, but the loading dock ventilation system prevents significant smoke migration to the rest of the garage area.

With no smoke control and the rolling doors open, Case NEL-9, smoke migrates into both stairs, and through the elevators at a rate approximately four times that as with the doors closed. The same applies to the general space in the B-1 level where the vision distance drops to about 12 ft in 30 minutes. Smoke spreads up through the elevator shafts to the core spaces in the building on all floors above the 9th, migrating to all three stairs.

A number of additional cases were simulated with different arrangements of the building fans to attempt to stop or restrict smoke migration. In no case was it possible to completely prevent any smoke from entering the towers under severe winter stack effect conditions. The best results were produced in Case NEL-15 where all of the return, exhaust and transfer fans serving the sub-grade areas of the towers and the lobby return fans were shut off. In this case the rolling doors are closed. Significant smoke intrusion is limited to the B-1 level. The maximum smoke density occurs 20 minutes into the fire. At 20 minutes, vision distance in the general B-1 area is reduced to about 75 ft. and some light smoke has entered the elevator shafts serving this floor but is diluted and significantly reduced in density as it reaches other levels. In less severe conditions (Case NEL-16) this arrangement of fans keeps Level B-1 clear of smoke. Under summer conditions this fan arrangement can exclude smoke even if the rolling steel doors are open.

A number of other cases (NEL-19, NEL-28 and NEL-29) were run to assess the possibility of managing smoke from a truck fire during severe winter conditions with the rolling doors open. No successful arrangements were found. In all cases where the rolling doors were open under conditions of winter stack effect (i.e., modeled as 15°F and wind conditions ranging from about 10 mph at the base of the complex to 60 mph across the roof of the towers) the smoke could not be held back but extended through significant portions of the affected building.

6.4 Impact of an Uncontrolled Fire

6.4.1 Fire in 1 WTC or 2 WTC

On rare occasions there have been uncontrolled fires of major consequences in modern office buildings. Examples include the May 1988 fire in the 60 story First Interstate Bank Building in Los Angles (Nelson, 1989) and the February 1991 fire in the 38-story, One Meridian Plaza Building in Philadelphia (Klem, 1991). Neither of these buildings was sprinkler protected at the time of the fire. To date there is no record of such an uncontrolled fire in a sprinkler protected building. In both the Los Angles and Philadelphia fires, the initial source fire would have been controlled by sprinklers.

For such a fire to occur in a WTC Complex office building once sprinkler protection is provided, it would require either that the sprinkler system was turned off or otherwise seriously impaired, or that a fire initiated in a fuel arrangement that produced a fire beyond the control capabilities of the sprinkler protection provided. Such a fire would also have to exceed the capabilities of the New York City Fire Department. The sprinkler system being installed in the WTC office areas is designed for office type occupancies. It is pertinent to note that in both the Los Angles and Philadelphia fires the fire department was seriously hampered by faults in the building standpipe and water supply system that seriously depreciated their ability to apply water from hose stream to the fire. It is understood that the standpipe systems in the WTC complex are regularly tested and in good order.

Testing of mobile shelving units at the National Research Counsel of Canada (Lougheed, 1994) demonstrated that mobile shelving unit of types currently promoted for office use can overtax sprinkler systems of the design being provided in the WTC office buildings. None of these storage units were observed during the site survey, but it is understood that the Port Authority does not have control over tenant installations of such devices. To the extent that the management of these buildings can prevent sprinkler interruption, and either prevent or provide special fire protection for mobile shelving or other unexpected fuel concentrations, the threat of an uncontrolled fire is not felt to be credible. The following analysis is designed to present the capabilities and limitations of various smoke control approaches if such a fire were to occur.

In both the Los Angles and Philadelphia fires, the fire initiated on one side of the building and progressed, breaking windows as it moved around the building until all of the windows on the affected floor were broken out. In each of these cases approximately an hour was involved in this phase of burning. While there is no certainty that an uncontrolled fire in the WTC would progress in the same manner, this is the best model available and has been used as the base condition in this analysis. The rate of heat release assumed is as shown in Figure 2.

Cases NEL-10, NEL-11, LAM-12A2 and LAM-13 demonstrate that under severe winter conditions without smoke control, an uncontrolled fire of the type modeled (i.e., having a rate of heat release as plotted in Figure 2) could readily spread heavy smoke and lethal concentrations of

carbon monoxide through the entire building above the lobby. Full fire buildup is predicted to require about 3 hours. Intolerable conditions would occur on the floors close to the fire and in the stairwell much earlier in the fire. The exact timing depends on the position of the doors between the fire source and the building core, and the extent of smoke passage through ceiling voids into the core area.

Case LAM-12C demonstrates that core pressurization alone will be incapable of managing the smoke from an uncontrolled fire with window breakage and a moderated wind impact on the broken windows.

Cases LAM-24, LAM-25, LAM-27, LAM-28, and LAM-29 illustrate another phenomenon that occurs when shutting off the supply fans to the fire floor. Smoke enters the supply ducts and spreads to other floors in that HVAC zone, and from them into the elevator and stair shafts in some cases. The fire dampers on the ducts will not operate in time to prevent the spread of significant levels of smoke. In order to prevent this spread of smoke, it is necessary to either pressurize the supply ducts to the fire floor (i.e., leave the supply fans running during the fire) or to install smoke rated dampers at every shaft penetration of the supply ducts. The often held view that leaving the supply fans operating during a fire would "fan" the fire does not apply to these buildings. The natural speed of air intake to the base of a fire plume is about 200 ft/min. Any air entering the fire plume at a lower velocity will not increase the natural burning rate of the fire. The flows that would occur in the towers due to the use of the supply fans to pressurize the ducts would not produce velocities in excess of 200 fpm at the base of a fire. Further, the large fire postulated in these cases cannot occur unless the windows break out. Once broken, the open windows would create a much more energetic flow than the HVAC system. Hence, there is no harm encountered from continuing the HVAC supply to the fire floor during a major fire. Rather, there is a clear benefit to leaving the supply fans operating to prevent the spread of smoke through the ducts and encourage more complete combustion, with resultant reduction in the generation of the toxic carbon monoxide. However, there can be, in the case of an uncontrolled fire, an increase of the flow of fire products, including flame, out the broken windows.

→ the installation of smoke rated dampers at shaft penetrations would be very expensive, and would not provide a demonstrably higher level of safety above that achieved by leaving the supply fans operating. This is not the case however, if a fire or [illegible] loss of electrical power to the fans.

A large number of cases were run to test the feasibility of using the various arrangements of the HVAC system to confine smoke to the floor of origin and keep the stairs clear of smoke should an

the portions of the stairwell below grade from that above grade. This stair is also interrupted at 76th Floor.

Stair pressurization in tall buildings presents special problems as a result of the stack effect and the impact of other shafts, primarily elevators, on the ability to pressurize a stairwell. Klote and Milke (1992) propose the following equation to estimate the height limit for stairwell pressurization.

$$H_m = K_m \frac{\Delta P_{max} - \Delta P_{min}}{\frac{1}{T_O} - \frac{1}{T_B}} \left(1 - \left(\frac{A_{SB}}{A_{BO}}\right)^2\right) \qquad \text{Equation 5}$$

where

H_m = height limit (ft),

ΔP_{max} = maximum allowable pressure difference between the stairwell and the building ("w.g.),

ΔP_{min} = minimum allowable pressure difference between the stairwell and the building ("w.g.),

T_O = outside design temperature (°R),

T_B = building temperature (°R),

A_{SB} = flow area between the stairwell and the building (ft^2),

A_{BO} = flow area between the building and the outside (ft^2), and

K_m = coefficient (0.131)

A calculation of the approximate height limit was made using Equation 5. The calculation was based on an outside temperature of 15°F, an inside building temperature of 70°F, a maximum acceptable pressure of 0.35" w.g., a minimum acceptable pressure of 0.05" w.g., a flow area between the stairwell and the building of 1 ft^2 per floor per stairwell and a flow area between the building and the outside of 2 ft^2 per floor. Equation 5 indicates a height limit of 224 ft or approximately 20 floors. Any change in criteria to reduce the design temperature difference or revise the pressure limitations will change the calculated height limit. Equation 5 does not consider the impact of the elevator shafts or wind forces on the building, both of which can increase the tendency of the stairwell system to exceed pressure limitations. The equation does,

however, provide explanation for the difficulty experienced in prior attempts by the Port Authority to develop stairwell smoke control for the stairwells in the towers.

As previously discussed, stair pressurization is not feasible in 1 WTC and 2 WTC. However, core pressurization will keep smoke out of the exit passageways for all expected fires once sprinklers are installed. In the unlikely event of an uncontrolled fire, the building fans can be used to place the building in the positive pressure ventilation mode to keep the stairs and elevators smoke clear. (See Section 6.4.1.) No other successful approach to stair pressurization was found.

6.6.2 Stairwells in 4 WTC and 5 WTC

All of the stairs in 4 WTC and 5 WTC are shorter than the height limit developed using Equation 5. Each of the stairs in these buildings except the north Stair in 4 WTC consists of interlocking (or scissors) stairs that are not aerodynamically separated.

An initial rate of air injection of 800 cfm per floor per stair (1600 cfm for the interlocking stairs) was tested using the CONTAM model. (See Figure 8.) Cases NELS-63D and NELS-63E cover the results for an exterior temperature of 15°F with wind conditions that produce an air speed of approximately 15 mph across the roof of this building. The 800 cfm per floor per stair flow rate worked well for the stairs in 4 WTC. Table 6.1 shows the results for each Stair with all doors closed except those on the 8th and 9th floors and at the exit level. This determined the lowest air flow which indicates a positive pressure with the doors open. It also indicates a range of pressures of 0.11 to 0.24" w.g. with all of the doors closed.

In 5 WTC, however, pressurization of the stairwell will not be as simple. In this building the flow needed to produce a positive flow on all floors was approximately 1,750 cfm per floor per stair (3,500 cfm per floor for interlocking stairs.) This resulted in significant over pressures (in some cases exceeding 1" w.g.) with the doors closed. Cases NELS-63A and NELS-63B form the basis for the results shown in Table 6.2. It is believed that the escalator openings and the

openings from 5 WTC into the Concourse cause this need for a high flow when doors are opened. It is, however, possible to successfully pressurize these stairs if a barometric relief or other means of relieving the over pressure when all the doors are closed can be provided.

Figure 8. Stair Pressurization Concept

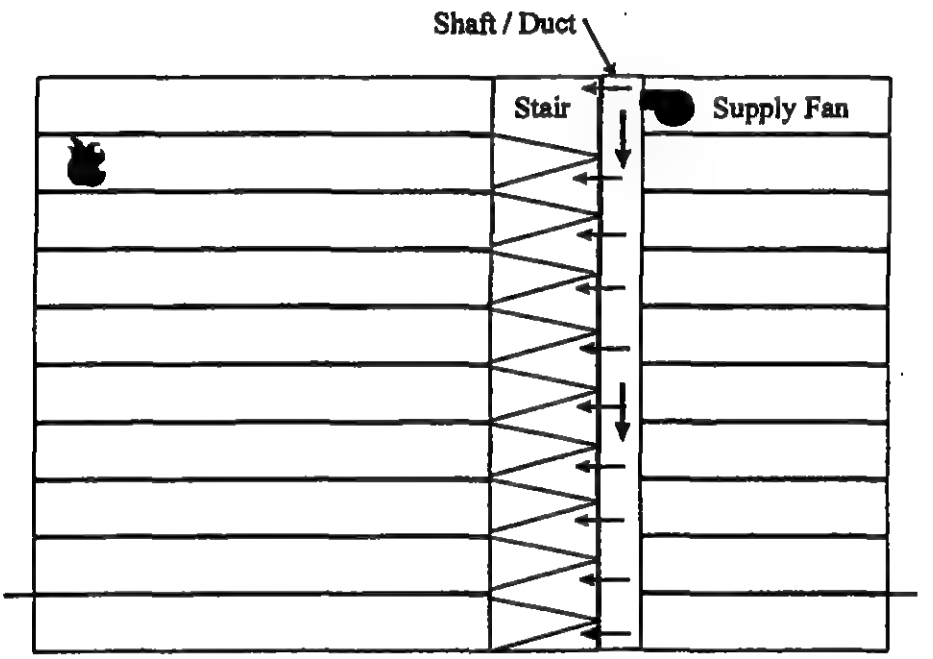


Table 6.1. 4 WTC Stair Pressurization Summary

Floor	Center Stair		West Stair		North Stair	
	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)
9	0.23	0.004*	0.12	0.004*	0.13	0.005*
8	0.23	0.005*	0,14	0.005*	0.13	0.005*
7	0.22	0.007	0.11	0.007	0.11	0.005*
6	0.22	0.008	0.11	0.008	0.11	0.006
5	0.22	0.008	O.11	0.008	0.11	0.006
4	0.22	0.008	0.11	0.008	0.11	0.007
M	0.22	0.01	0.11	0.01	0.11	0.007
P	0.21	0.001*	0.11	0.001*	0.11	0.005
C	0.24	0.009			0.14	0.007*
B-1						
B-2	0.22	0.007			0.11	0.007

* = OPEN DOORS

Table 6.2. 5 WTC Stair Pressurization Summary

Floor	West Stairs		Center Stairs		South Stairs	
	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)	Doors Closed ("w.g.)	3 Doors Open ("w.g.)
9	0.28	0.042*	1.13	0.037*	0.84	0.031*
8	0.19	0.025*	1.12	0.006*	0.87	0.004*
7	0.19	0.001	1.05	0.041	0.76	0.043
6	0.18	0.061	1.05	0.04	0.75	0.043
5	0182	0.033	1.04	0.012	0.75	0.016
4	0.17	0.027	1.04	0.005	0.75	0.011
M	0.19	0.039	1.07	0.019	0.78	0.025
P	0.31	0.013*	1.19	0.107	0.70	0.12*
C			1.22	0.129*		0.007*

* = OPEN DOORS

6.6.3 32 Floor HVAC Return Zone vs. 16 Floor HVAC Return Zone

Numerous cases were run to evaluate the effect of zoning of the HVAC system into 16 floor zones rather than 32 floor zones (typical), at the MER.

Cases LAM-29, LAM-29S, LAM-87, LAM-87S, LAM-88, LAM-88S, LAM-89, LAM-89S, LAM-89A, and LAM-89AS illustrate the impact of various arrangements of HVAC return system zoning. As discussed in Section 6.4.1, all of these Cases exhibited similar smoke movement performance in the model. That is, in each Case the model predicts that the smoke will be confined to the floor of fire origin. Given that there will be some time between the start of the fire, the completion of egress from the fire floor, and the breaking out of an exterior window and the initiation of the positive pressure ventilation mode of smoke control, it is expected that some smoke will migrate to other areas of the building (principally through the

un-pressurized supply ducts) before the positive pressure mode is activated. The model indicates that this migration will end upon activation of the positive pressure mode.

Since the positive pressure mode of smoke control is expected to over-pressurize the stair doors on the fire floor, special attention was given to the pressures developed on the stair doors to see if varying the number of floors in a return zone could lower the pressure differences. Tables 6.3, 6.4, and 6.5 show the pressure differences predicted across the stair doors, and across exit doors from the building on the Concourse and Plaza levels, at various levels in the tower. While there are clear differences between the pressures predicted between the 16 floor return zone and the 32 floor return zone, there is not a definable trend, especially when considering the effects of exterior weather conditions and height of the fire in the building. (Winter conditions were simulated as an outside temperature of 15°F and a westerly wind of 60 mph across the top of the towers. Summer conditions were simulated at an outside temperature of 90°F and an easterly wind of 60 mph across the top of the towers. In all of these cases, the west windows were broken out by the fire.)

Table 6.3. Pressure Differences (in. w.g.) and Door Opening Force (in lb.)* Across Door During Positive Pressure Ventilation Smoke Control Mode for a Simulated Uncontrolled Fire on the 9th Floor

	16 Floor Return Zone (9-25)			
	Winter (LAM-87)		Summer (LAM-87S)	
	Time 0:00	Time 1:30	Time 0:00	Time 1:30
Stair 1	0.006". 10.4 lb.	1.20" 80.4 lb.	0.03" 11.8 lb.	2.46" 154.4 lb.
Stair 2	0.008" 10.5 lb.	1.20" 80.4 lb.	0.04" 12.3 lb.	2.46" 154.4 lb.
Stair 3	0.040" 12.3 lb.	1.20" 80.4 lb.	0.11" 10.6 lb.	2.62" 163.7 lb.
Handicap door on 1	1.50" 98.0 lb.		2.50" 156.7 lb.	
Handicap door on 2	1.70" 109.8 lb.		2.30" 145.0 lb.	
Plaza doors on 2	1.80" 115.6 lb.		2.70" 168.4 lb.	

* Door opening force is calculated as described in Section 6.7.

Table 6.4. Pressure Differences (in. w.g.) and Door Opening Force (in lb.)* Across Doors During During Positive Pressure Ventilation Smoke Control Mode for a Simulated Uncontrolled Fire on the 25th Floor.

	16 Floor Return Zone (25-40)				32 Floor Return Zone (25-58)			
	Winter (LAM-89A)		Summer (LAM-89AS)		Winter (LAM-89)		Summer (LAM-89S)	
	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30
Stair 1	0.053" 13.1 lb.	1.30" 86.3 lb.	0.013" 10.8 lb.	2.57" 160.8 lb.	0.013" 10.8 lb.	0.833" 58.9 lb.	0.004" 10.2 lb.	2.07" 131.5 lb.
Stair 2	0.058" 13.4 lb.	1.30" 86.3 lb.	0.028" 11.6 lb.	2.56" 160.2 lb.	0.010" 10.6 lb.	0.831" 58.8 lb.	0.012" 10.7 lb.	2.07" 131.5 lb.
Stair 3	0.009" 10.5 lb.	1.35" 89.2 lb.	0.064" 13.8 lb.	2.68" 167.3 lb.	0.027" 11.6 lb.	0.850" 59.9 lb.	0.050" 13.9 lb.	2.14" 135.6 lb.
Handicap door on 1	1.53" 99.8 lb.		2.54" 159.0 lb.		1.03" 70.4 lb.		2.04" 129.7 lb.	
Handicap door on 2	1.77" 113.9 lb.		2.30" 145.0 lb.		1.27" 84.5 lb.		1.80" 115.6 lb.	
Plaza doors on 2	1.8" 115.6 lb.		2.74" 170.8 lb.		1.30" 86.3 lb.		2.23" 140.9 lb.	

* Door opening force is calculated as described in Section 6.7.8

It is possible to postulate a set of conditions where there is a benefit that can be derived from segregating the return air shafts into 16 floor zones. However, the smoke control settings that would result from such conditions would be exceedingly complex, and as such, less reliable. The recommended smoke control strategy for the rare, extreme, fire in a tower—Positive Pressure Ventilation—provides a simple and more reliable set of control settings, as well as effective management of the spread of smoke.

Table 6.5. Pressure Differences (in. w.g.) and Door Opening Force (in lb.)* Across Doors During Positive Pressure Ventilation Smoke Control Mode for a Simulated Uncontrolled Fire on the 86th Floor.

	16 Floor Return Zone (78-91)				32 Floor Return Zone (59-91)			
	Winter (LAM-29)		Summer (LAM-29S)		Winter (LAM-88)		Summer (LAM-88S)	
	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30	Time 0:00	Time 1:30
Stair 1	0.01" 10.6 lb.	1.18" 79.2 lb.	0.03" 11.8 lb.	0.28" 26.4lb.	0.004" 10.2 lb.	0.764" 54.8 lb.	0.038" 12.2 lb.	2.39" 150.2 lb.
Stair 2	0.01" 10.6 lb.	1.18" 79.2 lb.	0.01" 10.6 lb.	0.28" 26.4lb.	0.008" 10.5 lb.	0.760" 54.6 lb.	0.005" 10.3 lb.	2.36" 148.5 lb.
Stair 3	0.07" 14.1 lb.	1.24" 82.8 lb.	0.07" 14.4 lb.	0.29" 27.0 lb.	0.055" 13.2 lb.	0.838" 59.1 lb.	0.070" 14.1 lb.	2.43" 152.6 lb.
Handicap door on 1	1.62" 105.1 lb.		2.60" 162.6 lb.		1.08" 73.4 lb.		2.15" 152.6 lb.	
Handicap door on 2	1.87" 119.7 lb.		2.30" 145.0 lb.		1.32" 87.5lb.		1.91" 122.0 lb.	
Plaza doors on 2	1.9" 121.5 lb.		2.80" 174.3lb.		1.35" 89.2lb.		2.35" 147.9 lb.	

Door opening force is calculated as described in Section 6.7.8

6.7 Open Tenant Stairwell

The presence of open stairs between floors within the tenant spaces was confirmed by both observation and by report. Two separate cases are of interest. The first in the case where the stair is entirely within an HVAC zone. (i.e., the floors at the top and the bottom of the open stair are in the same HVAC zone.) The second case is where the stair crosses the zone boundary.

6.7.1 Within a Zone

Numerous cases were run with an open tenant stair between the 35th and 36th floors. No discernible effect was observed. The principal avenue of smoke spread in all cases where it spread beyond one floor were the many shafts in the buildings.

6.7.2 Breaching Zone Boundaries

Cases LAM-9, LAM-10, LAM-21, LAM-22, and LAM-23 were simulated to evaluate the effect of an open tenant stair breaching the HVAC zones. In cases LAM-9 and LAM-10, workstation fires were simulated on the floor both at the top of the tenant stair, and again at the bottom of the stair. No smoke control was simulated for these cases since prior cases had demonstrated that sprinklers effectively control the production of smoke under the workstation fire simulations. Minor air flow up the stair was noted in the simulations, but insufficient quantities of smoke were transported to the adjoining floor to obstruct vision. Similarly, dangerous levels of CO did not occur on the adjoining floor.

Cases LAM-21, LAM-22, and LAM-23 also show the effect of an open tenant Stair breaching the HVAC zones. In these cases, a total floor burn out was simulated on the floors at the top and bottom of the tenant stair (floors 24 and 25), as well as spreading from the lower floor to the upper floor (LAM-23). The smoke control strategy modeled in these cases included core pressurization on floors 9-24, and full pressurization (all supply fans on and all return and exhaust fans off) on all other floors in the building. This arrangement pressurized floor 25, the floor at the top of the open stair, and produced a strong flow down the stair from 25 to 24. Severe winter weather and wind conditions were included. In each of these cases, the smoke did not spread through the open stair. Rather, the smoke spread up the un-pressurized supply air ducts from the fire floor to the inside spaces on floors 20 to 25. We conclude that the effect of the open stair on smoke movement is minimal due to the pressurization possible with the HVAC system.

6.8 Pressurization of Elevators for Possible Use For Evacuation of Handicapped Persons.

As with the stairs, there is no practical way to pressurize elevators in the Tower buildings by direct injection of fresh air into the elevator shafts. Also, while on some floors vestibules are provided for freight elevators, this is not true on all floors and there is no space to install vestibules where none now exist. For this reason the pressurization of vestibules is not a viable approach.

As previously discussed, core pressurization, in 1 WTC and 2 WTC will keep smoke out of core and elevators for all expected fires once sprinklers are installed. In the unlikely event of an uncontrolled fire, the building fans can be used to keep the stairs and elevators smoke clear. See Section 6.4.1.

In 4 WTC and 5 WTC the above approach is not feasible. In each of these buildings the freight elevators have vestibules on all floors from the Concourse level to the top (9th) floor level. Analysis was made of the potential of using air injection into these vestibules as the means of excluding smoke from these spaces so that they could by developed into areas of refuge where handicapped persons could take shelter or evacuated using the freight elevators.

An initial estimate of the flow rate required was made using the orifice flow equation form contained in Klote and Milke (1992). The specific form of the equation used is presented as Equation 4.8a in their book and is as follows.

$$Q = K_f A \Delta P^{1/2} \qquad \text{Equation 6}$$

where

Q = volumetric flow rate through the path (scfm),

A = flow area (leakage area) (ft^2),

ΔP = pressure difference across path ("w.g.),

K_f = coefficient, 2610 ("w.g./ft-min)

An initial estimate of leakage rate, including the vestibule doors and doors to the elevators was 4 ft^2. To obtain the objective of a pressure difference of 0.1" w.g. the calculated flow is 3,300 cfm. Using this as the base, a number of trial and error runs were made with the objective of maintaining a minimum ΔP of 0.05"w.g. at each vestibule entry. The results indicate that an injection rate of approximately 3,000 cfm at each floor in 4 WTC and 4,000 cfm per floor in 5 WTC would be needed. Cases NELE-1A, NELE-1B, NELE-1C and NELE-1D cover these cases. The cases are based on an uncontrolled fire on one floor with a large number of windows on the windward side of that floor broken. One case in each building is based on winter conditions having an exterior temperature of 15° F and a wind impacting on the fire floor of 10 to 12 mph and another case where summer conditions of an exterior temperature is 90°F and no wind is present.

The calculated ΔP across the vestibule doors is shown in Table 6. All pressures are positive from the vestibule to the general building space. Since the intent is provide these spaces for the use of handicapped individuals, there is concern about the amount of force that will have to be applied to open the door to the "refuge area" once the smoke control air injection is initiated. Equation 4.18 from Klote and Milke (1992) was use to estimate the force involved for each of the cases. The equation is:

$$F = F_r + \frac{K_d W A \Delta P}{2(W - d)} \qquad \textbf{Equation 7}$$

where:

F = total door-opening force (lb),

F_r = force to overcome the door close and other friction (assumed to be 10 lb),

W = door width (assumed to be 3 ft),

A = door area (assumed to be 21 ft^2),

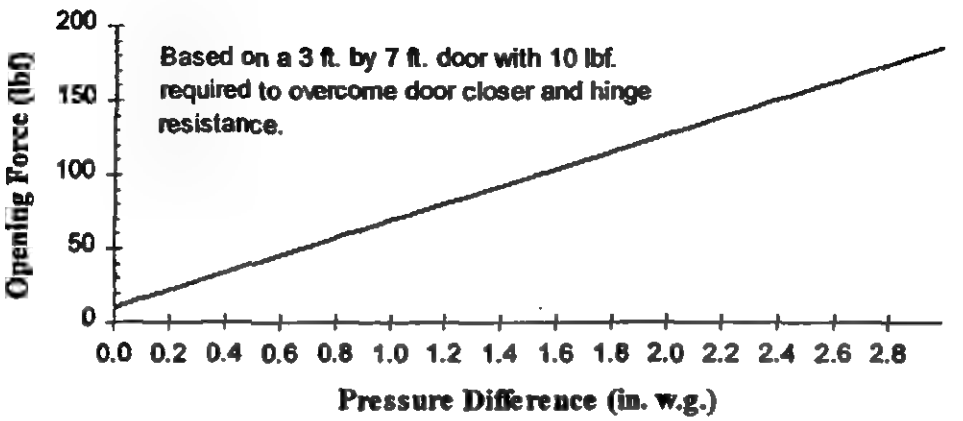
ΔP = pressure difference across the door ("w.g.),

d = distance from the doorknob to the knob side of the door (assumed to be 0.25 ft),

K_d = coefficient, 5.2. ($1/ft^2$-("w.g.).

The generic results of this calculation are shown graphically in Figure 9.

Figure 9. Door Opening Force



The calculated pressures and related opening forces for doors in 4 WTC and 5 WTC are shown in the following table.

Table 6.6 Calculated Pressure Differences and Door Opening Force for Elevator Vestibules

Case	Maximum		Minimum	
	Pressure ("w.g.)	Opening Force (lb)	Pressure ("w.g.)	Opening Force (lb)
NELE-1A 5 WTC, Winter conditions	0.30"w.g.	46 lb	0.12"w.g.	24 lb
NELE-1D 5 WTC, Summer conditions	0.24"w.g.	39 lb	0.19"w.g.	33 lb
NELE-1B 4 WTC, Winter conditions	0.28"w.g	42 lb	0.16"w.g.	29 lb
NELE-1C	0.17"w.g	30 lb	0.05"w.g.	16 lb

Some of the indicated opening forces are at level difficult for certain handicapped individuals to overcome. If this approach is used it may be necessary to provide barometric relief between the

"refuge area" and the general building area to limit the over pressure involved to 0.05"w.g. to 0.1" w.g. (i.e., opening forces of 9 to 15 lb.)

6.9 Fire Involving a Passenger Car in the Parking Garage.

A fire involving a passenger car was simulated at both the B-1 and B-4 levels. Section 3.3.3 describes the expected fire from a passenger car under sprinkler protection. Cases NELC-1 and NELC-2 are the car fire simulations in which winter conditions were assumed and no smoke control action was taken.

In each case the fire was controlled without any significant smoke migration beyond the garage level of origin. With the fire simulated at level B-1 the smoke level in the garage eventually reduced vision to about 2,000 ft. With the fire simulated at the B-4 level, that smaller garage did suffer vision reduction to about 150 ft but no significant migration to other spaces occurred.

6.10 Fire in PATH Terminal

A tracer fire (simulating a steady fire of about 20,000 Btu/s) was simulated in the portal to the PATH terminal to trace the potential movement of smoke from a large fire in the PATH terminal. Cases NELP-1, NELP-2, NELP-3 and NELP-4 address fire in the PATH terminal. In the "as is" situation without any smoke control under winter conditions, smoke migrated through most of the Concourse and into the tower buildings. When all of the return fans for the Concourse were simulated as shut down, the direction of flow in the Concourse changed and smoke migrated to the north east portion of the Concourse and all floors of 5 WTC. When sufficient return flows were shut down in the towers to prevent flow from the Concourse into these buildings, the smoke flow was reversed into the PATH terminal. In this case the smoke was forced down into the PATH system. An additional simulation was made replacing the trace fire with the kiosk fire discussed in Section 3.3.5. With this controlled fire, the migration of smoke was limited to a level that reduced visibility to about 100 ft in the portal and the nearby areas in the Concourse.

6.11 Impact of Shutting Down HVAC Upon Detection of Smoke.

New addressable smoke detectors are being installed in the return air plenums in the tower buildings. At the request of the Port Authority an analysis was made of the impact of shutting down the supply and return fans serving the portion (quadrant) of the Floor where detection occurs. In such case the shut down would stop both supply and return service to all of the floors served by the MER that serves the floor where detection occurs.

Cases NEL-73, NEL-74, NEL-75 and NEL-76 address this issue. Case NEL-73 simulates the base case where no fans are shut down. The simulated source fire was the office workstation in a sprinkler protected space. No smoke migration outside the quadrant of fire origin was indicated.

In cases NEL-74 and NEL-75 the same fire was simulated. In NEL-74 it was assumed that the compartmentation for the fire quadrant of origin was complete. In NEL-75 it was assumed that the smoke was free to spread to all quadrants and as a result would shut down all of the HVAC to occupant spaces (i.e., perimeter supply, interior space supply and interior space return.) In both of these cases some smoke migrated through the duct work of the shut down HVAC systems. Case NEL-76 simulated an uncontrolled fire as discussed in Section 6.4 and all of the HVAC supply for the entire HVAC zone shut down. The results indicate smoke spread from 15th Floor to roof Level is expected with high carbon monoxide concentrations throughout the floors near the source. This is essentially the same spread that occurred in other cases involving an uncontrolled burnout fire without any smoke control efforts. (See Cases NEL-10, NEL-11, LAM-12A2, and LAM-13).

These analyses demonstrate that shutting down the fans results in leaving the now un-pressurized duct work available for smoke migration. The analysis indicates that a better practice would be to go to the core pressurization upon detection of fire.

6.12 *Impact of Installing Revolving Doors on the World Financial Center Portal in One WTC Lobby*

The Port Authority is considering the installation of revolving doors in the portal to the World Financial Center in the lobby of WTC 1. Presently the leakage between this portal and the exterior is primarily determined by 6 doors. This portal was simulated in case NEL-4A to determine the expected flow under maximum stack effect conditions. (Defined as 15°F outside temperature with a 60 mph wind over the top of the building, with building HVAC systems set to Winter Normal.)

The amount of flow through the portal depends on the number of doors open. The CONTAM simulation was set to determine the flows and pressures estimated as entering WTC 1 from the portal and those entering from the Concourse to permit an analysis of the relationship of one to the other. In the simulation the six doors on the portal were progressively opened. As the area of opening increased, the pressure across the openings decreased and the flow from the portal into WTC 1 increased. At the same time, the flows into WTC 1 from the Concourse decreased. The flows and pressures determined by the model are shown in Table 6.~~12~~ 7

Table 6.~~12~~ 7 Flows Into WTC 1 from Portal and Concourse

Number of Open Doors in Portal	From Portal to WTC 1		From Concourse to WTC 1	
	Pressure (in. w.g.)	Flow (cfm)	Pressure (in. w.g.)	Flow (cfm)
1	0.78	26,000	0.77	124,000
2	0.69	52,000	0.73	120,000
3	0.64	75,000	0.69	111,000
4	0.60	95,000	0.65	107,000
5	0.56	114,000	0.62	103,000
6	0.53	132,000	0.58	100,000

The flow through the portal is concentrated in a single stream while the flow from the Concourse is divided among the 14 revolving doors, two handicapped doors, and the joint leakage's in the partition between WTC 1 and the Concourse.

Assuming that the leakage rates through six revolving doors and the associated partition would be approximately equivalent to that through a single open door, Table 6.7 illustrates that the installation of revolving doors in the portal could result in an increase in the present flow into WTC 1 from the Concourse by about 25% (from 100,000 cfm with six doors open to 124,000 cfm with revolving doors at the portal). This would increase the flow of smoke from a fire in the Concourse into WTC 1.

The recommendations in this report are, however, based on the worst case (i.e., all portal doors closed) since 2 WTC does not have a similar portal. This case represents the worst case since the flows into the lobby from the Concourse will be highest when the pressure differences across the barrier are the highest. Therefore, the installation of revolving doors would not make a significant impact on the flow of smoke from the Concourse into the lobby of 1 WTC. The installation of such doors would however reduce the overall stack effect in 1 WTC by increasing the resistance to infiltration into the building.

From the standpoint of smoke management, the presence or absence of revolving doors at the portal is a minor factor that does not change the overall smoke management approaches recommended. It may however, be desirable to install the doors since they would cut down on the infiltration into the building somewhat.

6.13 Egress Times and Exposure to Carbon Monoxide

The time to egress is based on the approaches detailed by Nelson and MacLennan (1995). In these buildings the time to egress is dominated by the throttling effects of the exit doors from the stairways. In each of the towers there are 3 stairs each having one 36 inch exit door. In 5 WTC there are 3 set of double stairs with each set having 2 exit doors for a total 6 exit doors. In 4 WTC there are two double and one single stairs with a total of 5 exit door from these stairs. The Port Authority indicates that the approximate population of the towers is 20,000 persons in each

tower. A population of 20,000 persons in a tower building represents at population density of approximately 200 ft^2/person. Applying this same density to 4 WTC and 5 WTC yields an estimated population, that would use the stairs for exit of about 2400 persons in 4 WTC and 2600 persons in 5 WTC.

The flow capacity of a 36 inch wide door is approximately 50 persons per minute when used to its maximum capacity (Nelson & MacLennan, 1995). Based on the preceding the minimum time to egress the several building would be approximately as shown in Table 6.~~9~~ 8

Table 6.~~8~~ 8. Minimum Exit Times

Building	Population	Number of Stair Exit Doors	Time to Egress through Exit Doors (min)
1 WTC	20,000	3	133 min
2 WTC	20,000	3	133 min
4 WTC	2,400	5	10 min
5 WTC	2,600	6	8 min

Experience in office buildings (Nelson & MacLennan, 1995) indicates that the actual egress time is always greater than the minimum exit time. This extra time is that used by factors such as investigation or query into the meaning of the alarm resulting in delayed start of egress, inefficiencies in using the stairs, and other factors. For buildings with an organized evacuation plan such as the WTC Complex, Nelson & MacLennan recommend that the actual expected egress time be assumed to be double the calculated minimum time. For purpose of estimating time that might be required for the last person to leave the building, a design time of 4 hours has been used for the tower building and 20 min for both 4 WTC and 5 WTC.

Depending on the size and location of the fire, persons evacuating one of the office building may be exposed to smoke and gases produced by that fire. The principle toxic species being carbon monoxide (CO). Tables ~~6-10, 6-11, and 6-12~~ 6.9, 6.10, and 6.11 show the extent of exposure to be expected by persons

using the stairways to exit the building. The levels are based on the calculated entry of smoke and gases into the stairwell during the time required to egress the building. The analysis makes the conservative assumption that at least one person may be within the stairwell for a period of time approaching the entire building egress time.

Table 6.9 Impact of CO exposure during evacuation from 1 or 2 WTC.

Smoke Control Approach	Maximum Carbon Monoxide Exposure in exit route (ppm)	Approximate Average Carbon Monoxide in Exit Route During Egress (ppm)	Potential Accumulated COHb (%)
Case NEL-11 Uncontrolled fire, 9th floor, Windward windows broken, No smoke control	11,000	1,215	> 50 (226) (Stairs potentially lethal)*
Case NEL-12 Sprinkler protected office fire, 9th floor, No smoke control	7	<1	<1
Case LAM-49 Uncontrolled fire, 55th floor, Windward windows broken, Positive pressure ventilation smoke control on.	None (No smoke migration into any exit route or off of floor of fire origin)	None	None

* This calculated value using Equation 2 does not consider human limitations. The indicated high concentration of COHb is a physiological impossibility, but shows that lethal conditions will develop in much less time than the expected egress time.

10

Table 6.[redacted] Impact of CO exposure during evacuation from 4 WTC.

Smoke Control Approach	Maximum Carbon Monoxide Exposure in exit route (ppm)	Approximate Average Carbon Monoxide in Exit Route During Egress (ppm)	Potential Accumulated COHb (%)
Case NELA-57 Uncontrolled fire on 8th floor, Windward windows broken,	28,000	1,442	35 (incapacitating) Smoke migrates into southeast portion of Concourse
Case NELA-60 Sprinkler protected office fire, 8th floor, No smoke control	None (No smoke migration into any exit route or off of floor of fire origin)	None	None
Case NELS-63D Stair pressurization	None	None	None

11

Table 6.[redacted] Impact of CO exposure during evacuation from 5 WTC.

Smoke Control Approach	Maximum Carbon Monoxide Exposure in exit route (ppm)	Approximate Average Carbon Monoxide in Exit Route During Egress (ppm)	Potential Accumulated COHb (%)
Case NELA-51 Uncontrolled fire on 4th floor. No smoke control	7800	5000	91 (lethal)* Smoke migrates through Concourse and into towers
Case NELA-60 Sprinkler protected office fire, 8th floor, No smoke control	None	None	None
Case NELS-63A Stair pressurization	None	None	None Smoke migrates through Concourse and into towers

* This calculated value using Equation 2 does not consider human limitations. The indicated high concentration of COHb is a physiological impossibility, but shows that lethal conditions will develop in much less time than the expected egress time.

As discussed in Section 2.0, Tenability, the criteria for acceptable CO exposure was set at 12% COHb. Purser (1995) sets the basis for incapacitation from CO exposure at about 30% COHb saturation in the blood stream, and death for healthy individuals at 50% COHb saturation. Both the incapacitation and lethal levels are believed to be lower in persons with compromised cardiac function. The use of the 12% criteria provides a safety factor for both such vulnerable persons and for the uncertainties in the prediction of the actual rate of CO generation in any fire.

The weather conditions for each of the case simulated for Tables 6.13.A, B and C was 15° F outside temperature with a 10 mph wind at grade and a 60 mph wind across top of building.

6.14 Relevance to NYC Building Code and NYC Fire Department Requirements.

The smoke control measures proposed in this report are in line with the requirements of Section 4-2, Smoke Control - Special Situations, of NYC Building Code Reference Standard Reference RS 13, Mechanical Ventilation, Air Conditioning and Refrigeration Systems. Specifically the approaches in this report are felt to meet the requirements of Section 4-2 that reads:

> A building ... in which it is determined that evacuation time is excessive ... shall have the duct systems arranged so that, in the event of a fire, flow of smoke from the fire zone will be inhibited from spreading to required interior ways of exit access, interior enclosed stairs and ramps, interior exit passageways and designated refuge areas. Such an arrangement may involve air conditioning systems alone or in combination with other systems such as emergency venting and fire suppression, taking into account stack and wind effect of multistory buildings. Smoke control systems are required to be engineered for the specific occupancy and building design.

The justification for the smoke control approaches proposed in this report are based in the above requirement.

A second issue is the desire of the NYC Fire Department that the activation of smoke control measures not be initiated until so ordered by the fire officer in command at the time of a fire. This report proposes that the initial smoke management action, core pressurization in the towers, pressurization of the tower basement area if smoke from a truck dock fire is detected within the tower perimeter, and stairwell pressurization for 4 WTC and 5 WTC be initiated as soon as a fire is detected. It is our opinion that this early response of these smoke control efforts is necessary for the best level of occupant safety and needed to conform with Section 4-2 of Reference Standard 13, as quoted above. It is also our analysis that the amount of air movement at this stage of smoke control is insufficient to affect the rate of burning.

This report proposes a second emergency level of smoke control involving positive pressure ventilation. This level is to be used only if an uncontrolled fire has reached such proportions that windows are being broken out by the fire and then only with the concurrence of the fire officer in command. This approach, of course, is in concurrence with the Fire Department's desires.

7.0 Conclusions

As a result of the analyses conducted, the following conclusions are drawn.

1. Sprinkler Protection

The analysis in this project along with those in the previous project, Smoke Management Evaluation Study of The World Trade Center Concourse and Plaza (Hughes, 1996) show that, with the several exceptions noted herein, the provision of sprinkler protection will allow only minor smoke migration from the space of fire origin. All of these analyses of sprinklered fires indicate that exit paths, stairs and elevators will remain sufficiently free of smoke to be safely used for building egress. In these cases, persons proximate to the fire may have to evacuate the space of fire involvement but can find safe refuge in the core area or on an adjacent floor.

2. Stairwell Protection in Towers

As discussed in Section 6.5.1, the height of the towers and the tower stairwells precludes effective traditional stair pressurization of major portions of the stairs by air injection. The protection of the stairs from smoke intrusion can be accomplished, however, by core pressurization in the expected cases and by positive pressure ventilation in the unlikely event of an uncontrolled fire. See Section 6.4.

3. Core Pressurization Smoke Control in Towers

The vast majority of anticipated fires in the towers will be small and controlled by the sprinkler system. In these cases, setting the HVAC systems to the Core Pressurization configuration (See Figure 6) will contain the smoke in the area of fire origin, and prevent the spread of dangerous levels of smoke and contaminants into the core, the stairwells, and the elevator shafts.

4. Positive Pressure Ventilation of Towers

As noted in the analysis, it is possible to hypothesize a fire of major magnitude that could involve an entire floor in one of the Towers. Such fires have occurred in office buildings without sprinkler protection, but to date we are unaware of any that have occurred in a sprinkler protected office facility. A fire involving an entire floor was used in this study to assess the potential of developing smoke management systems capable of withstanding the most severe exposure.

In the unlikely event that an uncontrolled fire develops, it is possible to use the HVAC fans to provide smoke control for the tower buildings, once that fire breaks out windows. The approach involves positive pressure ventilation. (See Figure 7) This approach as described in Section 6.4.1 is designed to keep both stairwells and elevators clear of smoke and toxic gases. The use of these fans under these conditions can result in pressures on the fire floor stairwell doors that would prevent any persons still on that floor from escaping. It should never be used until that floor is clear of occupants, and only under the direction of the fire officer in charge of the incident.

5. **Stairwell Smoke Control, 4WTC**

In 4 WTC it is possible to use air flow, either provided by dedicated fans or diverted into the stairwell from the building system, to pressurize the stairwells sufficiently to exclude smoke from the severe winter fire condition described above. This can be accomplished while not over-pressurizing the stairs.

6. **Stairwell Smoke Control, 5 WTC**

In 5 WTC is possible to use air flow as in 4 WTC to pressurize the stairwells. However, the air flow needed to provide for pressurization with up to 3 doors open can over-pressurize the doors when all of the doors are closed. For such a system to work in 5 WTC, it will be necessary to provide a nearly instantaneous pressure control device, such as barometric dampers. This is necessary to assure sufficient pressure when doors are open and prevent over pressurization when all doors are closed.

7. **Smoke Control for Elevators, 4 WTC and 5 WTC**

In both 4 WTC and 5 WTC there are vestibules outside the entrances to the freight elevators on each of the office floors. Simulations using air flow to pressurize these vestibules indicated that it is feasible to use air injection into these spaces to provide "areas or refuge" for handicapped individuals to be removed from the building via these elevators. In 5 WTC, the model indicates that it is necessary to inject 4,000 cfm into the vestibule on each floor. In 4 WTC, the model indicates that it is necessary to inject 3,000 cfm into the vestibule on each floor.

8. **Smoke Flow into Concourse**

If the hypothesized severe winter fire occurs in 5 WTC, the analysis indicates that the smoke will spill out of that building into the Concourse and across the concourse into the tower buildings. The analysis indicates that this flow can be restrained if one of the following options is employed:

a) The entire concourse and the towers are placed in a pressurization mode by shutting off the return and exhaust fans serving the Concourse and a sufficient number of return fans in the Towers to prevent flow from the Concourse into the Towers, or

b) Install doors that will be closed at the time of a fire to separate the Concourse and Plaza level entrances from 5 WTC to the Concourse, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8, or

c) Install doors that will be closed at the time of a fire on the escalator, and pressurize the stairs and freight elevator vestibules as described in Section 6.5.2 and 6.8.

Option (a) will confine the smoke to the floor of origin, keeping the exit routes clear throughout the fire. Options (b) and (c) will permit smoke migration into the lobbies on all floors below the fire floor, with some migration into the adjacent area of the Concourse, but the exit routes will remain clear.

9. Fire in PATH Terminal

A minor, sprinkler controlled, fire in the PATH terminal would result in local smoke and minor spread to those portions of the Concourse nearest the PATH entrance. In case of a major fire in the PATH terminal, without either sprinkler suppression or smoke control, smoke would spread widely over the entire Concourse and into the tower buildings. To prevent this it would be necessary for the entire Concourse to be placed in a pressurization mode, by shutting down return and exhaust fans serving the Concourse and adjusting the fans in the towers to prevent air flow from the Concourse into the towers. If this were done, however, the smoke from the fire would be forced into the PATH terminal and system.

10. Truck Fire at Loading Dock

If a fire develops in the cargo compartment of a large truck, shielded from the garage sprinkler protection, a serious condition of smoke migration into the

adjacent tower can occur. With the combination of open loading dock doors and no smoke control in the tower, smoke can spread into the B-1 level. With the loading dock doors closed and the sub-grade levels and the lobby return fans off, smoke can be controlled, even on a severe winter day. The loading dock doors should be kept closed or arranged to close automatically in the event of a fire.

11. Tower Lobby Fire

The lobby HVAC system has the capabilities to be used as an atrium smoke control system to keep the exits through the lobby of a tower passable given a large (11,000 Btu/s) fire in the lobby. Under severe winter conditions it would be necessary to shut down sufficient supply fans in adjacent zones to prevent stack effect flows up the elevators from diverting smoke into the elevator shafts.

12. Passenger Car Fire in Garages

A fire involving a passenger car in the garage would not result in significant smoke migration into the adjacent buildings or obstruct egress from the garages.

13. Impact of Shutting Down Fans Upon Smoke Detectors

Shutting down fans on smoke detection is less effective in terms of smoke control than leaving the fans on and spilling all of the return and setting the supply on 100% outside air.

14. Interrelationship of All Elements of WTC Complex

The analyses in this project re-enforce the fact that all of the HVAC systems in the entire complex interact significantly. Any major changes in one portion of the facility may impact other portions of the facility, potentially affecting the movement of smoke from a fire. The most significant impact is that produced by the PATH system on the Concourse and 5 WTC. Other impact could result if separate sections of the complex, such as one or more office building, were placed under separate HVAC management from the complex as an entity.

8.0 Recommendations

As the result of this study, the following recommendations are submitted.

1. Sprinkler Protection (Entire Complex)

Complete the program for total automatic sprinkler protection of the entire complex. Where spaces are known to be used for storage or track files or other high concentrations of potential fuel for a fire, provide extra protection in the form of additional suppression capabilities (i.e. increased discharge density from the sprinkler system), fire resistive enclosure of the space involved, or both.

2. Emergency Smoke Management Sequence In Tower Buildings

The following sequence of actions is recommended in case of a fire in one of the towers.

a) Notify the NY City Fire Department and follow the WTC emergency procedures for the floor involved and adjacent floors.

b) Upon activation of any smoke detector or sprinkler system, set the HVAC system covering the entire zone where the fire is detected to core pressurization.

c) If smoke detectors involving 2 or more detectors on floors other than the fire floor occurs, evacuate all floors served by the MER serving the fire floor that are on the same side of the MER floor as the fire floor; that is all floors served by the same supply fans that serve the floor of fire involvement.

3. Handling An Uncontrolled Fire in a Tower

While an uncontrolled fire is an unlikely event, it is prudent to provide contingency plans for smoke protected egress and refuge in case of such an event occurs. Plans to institute positive pressure ventilation as described in Section 6.4.1 should be developed and

coordinated with the New York City Fire Department and regularly rehearsed and tested. Implementation of positive pressure ventilation by its nature is a fire ground action and would be implemented under the direction of the fire officer in charge with advice and assistance from the WTC engineers.

4. Smoke Control for Stairs and Elevators, 4 WTC and 5 WTC

It is recommended that pressurized smoke control be considered for the stairs and the freight elevator vestibules in 4 WTC and 5 WTC. (i.e., a dedicated fan system injecting air at multiple points in the stairs and into the vestibules each floor.) As discussed in the analysis, barometric relief or other pressure relief will be needed in the stairs for 5 WTC. The recommended operating sequence is to initiate the Stair and vestibule pressurization upon activation of more than one detection of smoke in the plenum space. To lessen the circulation of smoke through the HVAC ducts, the HVAC system should not be shut down but set to total outside air with no recirculation.

5. Additional Area of Refuge Design Elements, 4 WTC and 5 WTC

The pressurization of the freight elevator vestibules is intended to provide the basis for "areas of refuge" for handicapped persons. If the Port Authority elects to use these vestibules for this purpose it will be necessary to:

a) Equip all of the vestibule doors with door closers triggered by the activation of the smoke control system.

b) Provide the necessary signage and communications system to identify the spaces as areas of refuge and enable anyone in the areas of refuge to communicate their location and needs to the WTC emergency control location.

c) Recall the elevators serving the vestibules to the exit floor and place them in emergency service. The accessible egress paths usable by a mobility impaired person is via the elevators serving these vestibules exiting at the Concourse or B-2 levels. Both of these routes are potentially exposed to blockage by smoke, though the likelihood of both being blocked is improbable, as demonstrated by the

analysis in this report. For this reason it will be necessary to know the condition of the egress routes before evacuating anyone using the elevators. Evacuation should then be controlled by an emergency operator who is aware of any smoke in the exit routes and can act accordingly.

6. Keeping Smoke Confined to 5 WTC

A special problem exists in case of a severe fire in 5 WTC. If, in event of fire, the smoke detectors indicate smoke in three or more smoke detection zones, it is possible that a fire overtaxing the sprinkler system has occurred. In this case there is a danger of smoke spreading into the Concourse and tower buildings. To counter this, if such a warning occurs, all of the returns from the Concourse HVAC systems should be shut down. If such a fire occurs under winter conditions, return fans in the towers will also have to be shut down to keep smoke within the perimeter of 5 WTC. Other approaches to controlling the smoke from a fire in this building were modeled (See Section 6.4.2), but none exhibited the same level of safety in 5 WTC and the Concourse open to it.

7. PATH Terminal

The Port Authority needs to continue its studies of smoke management in the PATH terminal. A minor, sprinkler controlled fire in the terminal would not present a serious hazard. A major fire, typified by a PATH car fire could, however, expel smoke into the Concourse, migrating either into the towers or into 5 WTC. The smoke could be held back by shutting down all Concourse return fans and sufficient return fans in the towers so that air flow is from the tower lobbies into the Concourse. If this were done, however, the smoke would be forced into the terminal and the PATH system itself. We understand that Port Authority Engineering has completed a preliminary design for the PATH Terminal smoke management system that is compatible with the criteria, assumptions, and findings of this study.

8. Interrelationship of PATH Terminal and Complex

It is important, however, that no solution that involves the closure of the PATH terminal from the Concourse be considered without evaluation of the effect of that closure on smoke

movement in the Concourse. The PATH terminal is a major source of air that avoids a winter condition where the towers could impose a negative force on 4 WTC and 5 WTC.

9. Loading Dock Smoke Control

Damage to the doors between the loading dock and the tower building should be repaired. The rolling steel doors should be equipped with smoke detectors, arranged to close these doors if they should be open and a fire occurs at the dock. Additionally, if two or more smoke detectors in the return air from the B-1 space are activated, the supply to the sub-grade portions of the tower involved and the supply to the lobby of that tower should be shut down.

10. Tower Lobby Smoke Control

In case of fire in the lobby of one of the towers, the lobby supply and return should be continued in operation with no recirculation and 100% fresh air supply and 100% exhaust of the return. In winter conditions the core returns for floors 1 to 6 and sub-grade areas should be shut down. Additional returns should be shut down until any flow from the concourse or outside into the lobby is mitigated. To implement this it is recommended that a pressure sensors be installed in each of the tower lobbies that measure the pressure difference between the lobby and the Concourse and between the lobby and the exterior. The data from these reading should be shown in the control room.

11. Further Tests

Tests of the proposed procedures should be conducted under both summer and winter extreme conditions prior to implementation of this study to verify the pressures predicted by the model. The procedures recommended above are based on calculations using the model CONTAM96. As such they involve the use of selected field measurements and assumptions relative to specific leakage paths and dimensions. It is felt that pressure differentials and pressures applied to doors in the means of egress are the key measurements. The use of smoke tracers, while not considered essential, could be of assistance in discovering unanticipated leakage paths.

9.0 References

ASHRAE, 1989

ASHRAE Handbook - Fundamentals, American Society for Heating Refrigeration and Air Conditioning Engineers, Atlanta, GA, 1989.

Babrauskas, 1995

Babrauskas, Vytenis, "Burning Rates," Chapter 3-1, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

BHP, 1987

BHP Melbourne Research Laboratories, "Fire in Closed Carpark Buildings," BHP Melb. Res. Lab. Rep. No. MRL/PS98/87/001, September, 1987.

Caro, 1995

Caro, Tony C., and James A. Milke, "A Survey of Fuel Loads in Contemporary ONice Buildings," University of Maryland Department of Fire Protection Engineering, for NIST, November, 1995.

ECCS, 1993

European Convention for Constructional Steelwork, Technical Committee on Fire Safety, "Fire Safety of Open Car Parks," Technical Note No. 75, Draft, March, 1993.

Hughes, 1996

Hughes Associates, Inc., and Dillon Consulting Engineers, Inc., "Smoke Management Evaluation Study of the World Trade Center Concourse and Plaza," Port Authority of New York and New Jersey, May, 1996.

Klem, 1991

Klem, Thomas J., "High-Rise Fire Claims Three Philadelphia Fire Fighters," *NFPA Journal*, September/October 1991, p. 64.

Klote and Milke, 1992

Klote, J.H., and Milke, J.A., *Design of Smoke Management Systems*, American Society for Heating Refrigeration and Air Conditioning Engineers, Atlanta, GA, 1989.

Lougheed, 1996

Lougheed, G. D., personal communication.

Lougheed, 1994

Lougheed, G.D., J.R. Mawhinney, and J. O'Neill, "Full Scale Tests and the Development of Design Criteria for Sprinkler Protection of Mobile Shelving Units," *Fire Technology*, 30 (1), 1994, pp. 98-133.

Madrzykowski, 1992

Madrzykowski, Daniel, and Robert L. Vettori, "A Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System," NISTIR 4833, National Institute of Standards and Technology , May, 1992.

Mangs, 1994

Mangs, J., and O. Keski-Rahkonen, "Characterization of the Fire Behavior of a Burning Passenger Car. Part I: Car Fire Experiments," *Fire Safety Journal*, 23, 1994, pp. 17-35.

Mitler, 1996

Mitler, H. E., The Burning of a Merchandise Kiosk," National Institute of Standards and Technology. (Personal communication, report to be published.)

Mulholland, 1995

Mulholland, George W., "Smoke Production and Properties," Chapter 2-15, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Nelson and Forssell, 1994

Nelson, H.E., and Forssell, E.W., (1994), "Use of Small Scale Tests in Hazard Analysis," *Fourth International Symposium on Fire Safety Science, International Association for Fire Safety Science*, 1994, pp 971-982.

Nelson and MacLennan, 1995

Nelson, H.E., and MacLennan, H.A., "Emergency Movement," Chapter 3-14, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Nelson, 1989

Nelson, Harold E., "An Engineering View of the Fire of May 4, 1988 in the First Interstate Bank Building, Los Angeles, California," NISTIR 89-4061, National Institute of Standards and Technology, March, 1989.

Nelson, 1989

Nelson, Harold E., "An Engineering Analysis of Fire Development in the Hospice of Southern Michigan, December 1985," Fire Safety Science-Proceedings or the Second International Symposium, 1989.

Nelson, 1990

Nelson, Harold E., "FPETOOL: Fire Protection Engineering Tools for Hazard Evaluation," NISTIR 4380, National Institute of Standards and Technology, March, 1990.

Purser, 1995

Purser, David A., "Toxicity Assessment of Combustion Products," Chapter 2-8, *SFPE Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Shipp, 1995

Shipp, Martin, and Michael Spearpoint, "Measurements of the Severeity of Fires Involving Private Motor Vehicles," *Fire and Materials*, 19, 1995, pp. 143-155.

Tamura, 1994

Tamura, George T., *Smoke Movement and Control in High Rise Buildings*, National Fire Protection Association, Quincy, MA, 1994.

Tewarson, 1995

Tewarson, A., "Generation of Heat and Chemical Compounds in Fires" Chapter 3-4, *Handbook of Fire Protection Engineering*, Ed. DiNenno et al., 2nd Edition, NFPA, Quincy, MA, 1995.

Appendicies

Eventual Outputs

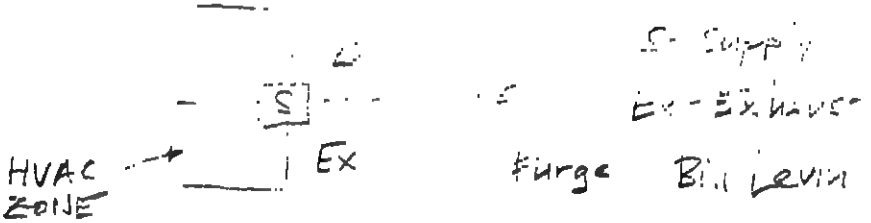
1. Test Data
2. Building Data

Stairway Pressurization 4 & 5
Stairway Pressurization 1 & 2
Sandwich Zones
Smoke-protected elevators

Field Testing

Tall Bldgs

VAV Variable Air Volume Dampers



- Calibrate instruments
- Boundary conditions (summertime results) at the Concourse
- 90% sprinklered

Mr. Steven Weiner, PE
The Port Authority of NY & NJ, Rm 1961
One World Trade Center
New York, NY 10048

RE: Site Visit and Field Testing

Dear Steve:

As we discussed we are planing the site visit and field tests for June 29th through July 2nd. As you requested, I will arrive on JUNe 28th. I plan to be in your office by about 10 AM.

The following is our general plan.

1. FLOW TESTS USING BUILDING HVAC SYSTEMS.

We plan to conduct extensive testing in 2 WTC and 4 WTC, with limited confirmation testing in 1 WTC and 5 WTC. We will have to decide what, if any, testing will involve the Sub-grade areas after we arrive. We desire to conduct the following tests. We hope to use 3 teams to take the readings involved.

2 WTC.

a. Shut down of all possible fans, other than those that recirculate air in tenant spaces. We realize that some air flow may be needed for safety or process reasons, but the more we can shut down the more accurate the results. With the building in this state we will take readings of outside temperature and air speed and the pressure drops at elevator shafts, stairwells, and possibly other points, such a telephone equipment cabinets and electrical panels at up to 30 floors in the building. The actual number will depend on the level of variation between test locations.

b. Shut down the supply to a air supply zone in the top section of the building, place that section on total exhaust and to the maximum extent possible place the entire rest of the building on supply without return. Again take measurements throughout the building.

c. Repeat the process with the building in the "purge" mode that currently would be used for smoke management.

d. Repeat the process in the middle section of the building. If the reading are similar to those take in the top section, the number of readings will be reduced.

e. Repeat the process in the lower section of the building. Again, if the readings are consistent the number taken will be reduced.

f. Repeat the process in the lobby.

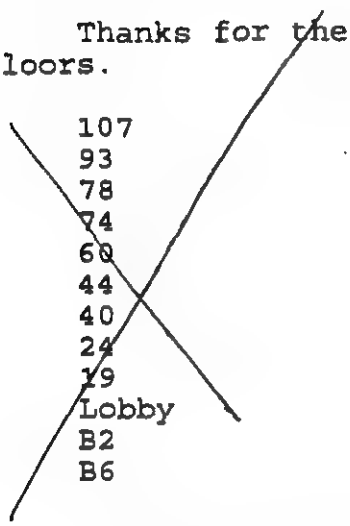
FAX

TO: Tony York, PANY&NJ, 1 WTC, Rm 1961
Phone 212 435-8916
FAX 212 435-8826

FROM: Bud Nelson, Hughes Assoc., Inc 6/24/96
Phone 410 737-8677
Fax 410 737-8688

SUBJ: Test Sites, 2 WTC

Thanks for the diagram. I suggest testing on the following floors.



NOTE: Transmitted verbally, not actually sent.

Mr. Steven Weiner, PE
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The following is our general plan.

1. FLOW TESTS USING BUILDING HVAC SYSTEMS.

We plan to conduct extensive testing in 2 WTC and 4 WTC, with limited confirmation testing in 1 WTC and 5 WTC. We will have to decide what, if any, testing will involve the Sub-grade areas after we arrive. We desire to conduct the following tests. We hope to use 3 teams to take the readings involved.

2 WTC.

a. Shut down of all possible fans, other than those that recirculate air in tenant spaces. We realize that some air flow may be needed for safety or process reasons, but the more we can shut down the more accurate the results. With the building in this state we will take readings of outside temperature and air speed and the pressure drops at elevator shafts, stairwells, and possibly other points, such a telephone equipment cabinets and electrical panels at up to 30 floors in the building. The actual number will depend on the level of variation between test locations.

b. Shut down the supply to a air supply zone in the top section of the building, place that section on total exhaust and to the maximum extent possible place the entire rest of the building on supply without return. Again take measurements throughout the building.

c. Repeat the process with the building in the "purge" mode that currently would be used for smoke management.

d. Repeat the process in the middle section of the building. If the reading are similar to those take in the top section, the number of readings will be reduced.

e. Repeat the process in the lower section of the building. Again, if the readings are consistent the number taken will be reduced.

f. Repeat the process in the lobby.

3. 4 WTC

The process will be similar for this building as with 2 WTC except that the building will be treated as a single HVAC zone. One test will be made with fans down and one with the fans in the supply mode only. In this building special attention will be given to the flows at the escalator openings.

4. 1 WTC & 5 WTC

In both of these buildings sample tests will be made to determine if the readings in 2 & 4 WTC can be assumed to apply in these building as far as expected leakage rates. If not, additional test will be made to produce a reference basis for estimating leakage rates and proofing the results of the model.

We estimate that, with your help, the above tests can be conducted in 12 to 16 hours over 2 to 3 nights. We expect to conduct them in hours when the buildings are at there lowest level of use. We will need your help to control the fans, gain access, and take measurements.

5. SUB-GRADE LEVELS

For each building test conduct pressure difference measurements across all boundaries.

6. ADDITIONAL DATA

a. Tenant Stairs. These stairs can have an important impact on smoke movement. We need to identify where they are, if they are enclosed and how far they reach. If two or more are on the same floor we need to determine if they are separated by a smoke resisting barrier. Possibly your rental unit might be able to supply this data.

b. Elevator Shafts. As you know, elevator shafts are the single most important means of smoke movement in tall buildings. We will need to establish each shaft, the cars in the shaft, the extent of the shaft (level of lowest shaft opening and top of shaft, and the size and method of shaft venting. It would be helpful if we could meet with your elevator engineering staff (or contractor) on this.

c. HVAC Shafts. We understand that return air shafts are used in these buildings. We need to know the details of there size and the form and location of the top and bottom terminations.

d. FANS (MER's). We will need the mechanical plans for each of the MER's or other fan locations in each building and serving the sub-grade areas. We will also need the latest test and balance information that the Port Authority has for these buildings.

e. FLOOR LAYOUTS. We will need the layout to model the space relationships. We will need a complete set of the most up-to-date half size architectural drawings for all floors, sections and elevations of 1, 2, 4, & 5 WTC and the sub-grade areas. It may be possible to get supplement the data we need from tenant assignment drawings. The transfer of this data to the model will be a major work load in the project. We will need to bring the appropriate plans back to our offices.

f. EXIT STAIRS. We will abstract the stair layout from the floor layouts and will collect the details during the site visit.

g. DAMPERS, LOUVERS, ETC. We will need access to the main air flow controlling dampers with the ability to open and close them and measure the size when open and the leakage gaps when closed.

Key to the efficient physical testing will be the cooperation of the Port Authority and communications during the tests. Can you obtain several radios (4 if possible) that can communicate within the WTC complex. Also key will be ready access to all areas where tests will be run or spaces or elements inspected, measured or recorded. As in the previous phase we plan to take extensive photographs and videos.

Once Tony returns from his honeymoon, please contact me and we will set up a conference call between us and Mike Dillon to detail these plans and determine what support we can get form the Port Authority and how we will proceed.

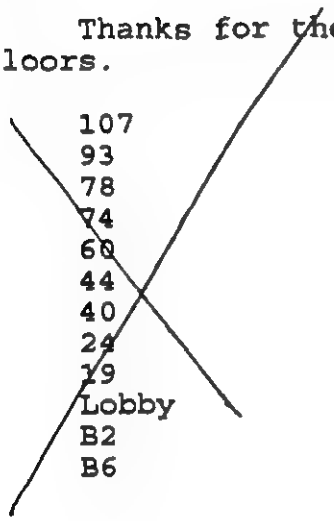
FAX

TO: Tony York, PANY&NJ, 1 WTC, Rm 1961
Phone 212 435-8916
FAX 212 435-8826

FROM: Bud Nelson, Hughes Assoc., Inc 6/24/96
Phone 410 737-8677
Fax 410 737-8688

SUBJ: Test Sites, 2 WTC

Thanks for the diagram. I suggest testing on the following floors.

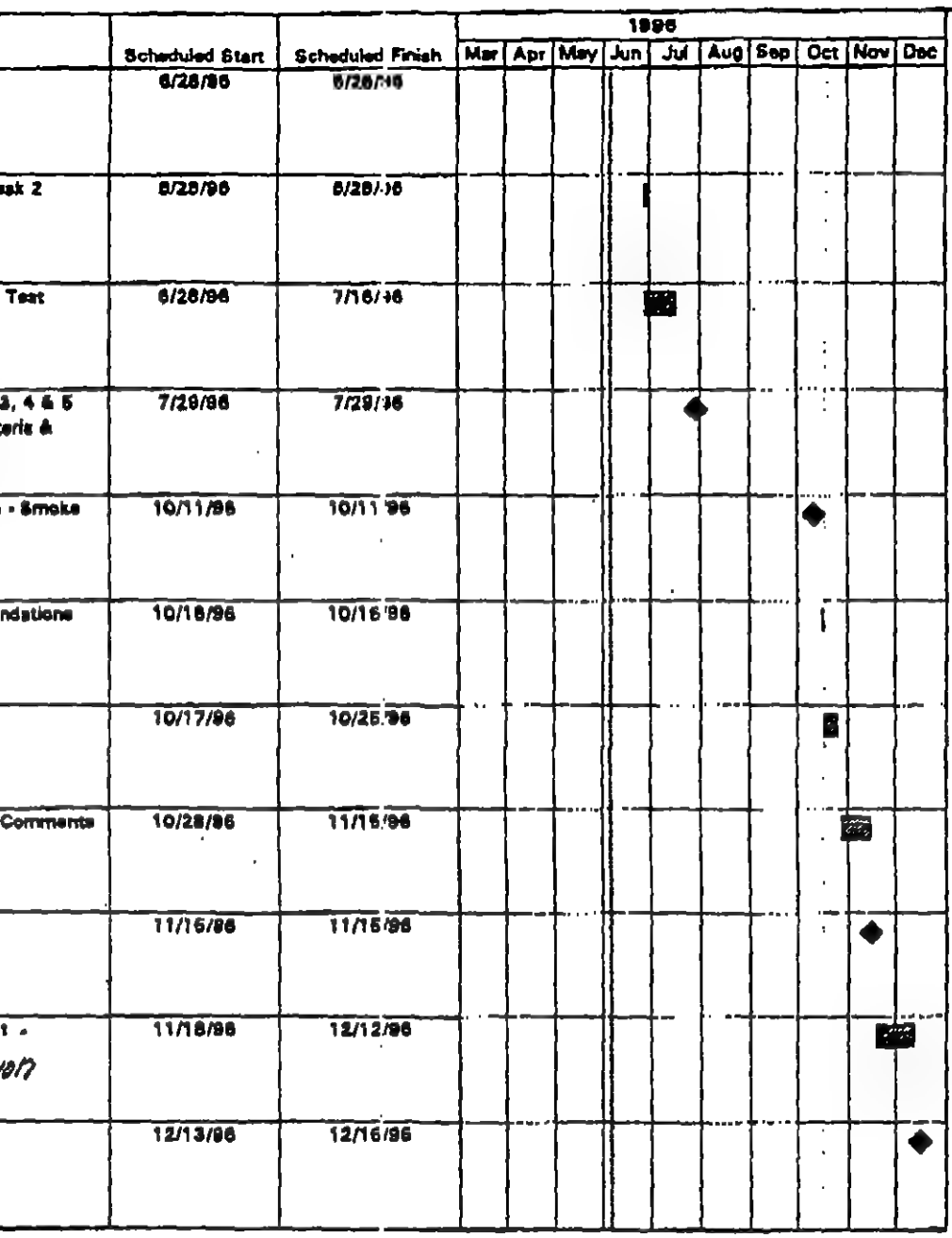


NOTE: Transmitted verbally, not actually sent.

DRAFT 6-5-96

WTC - Smoke Management Evaluation Study
for the Entire WTC Complex
CWO2-928.010

ID	Name	Scheduled Start	Scheduled Finish
13	Kick-Off Meeting	6/28/96	6/28/96
14	Develop BL Schedule, Task 2	6/28/96	6/28/96
15	Task 3 - Phys. Survey & Test	6/28/96	7/16/96
16	Program Report - Tasks 3, 4 & 5 Field Survey, Design Criteria & Diag's., Fire Scenarios	7/29/96	7/29/96
17	Program Report - Task 6 - Smoke Migration Analysis	10/11/96	10/11/96
18	Draft Report - Recommendations	10/16/96	10/16/96
19	PA Review	10/17/96	10/25/96
20	Consultant Incorporates Comments	10/28/96	11/15/96
21	Final Report	11/16/96	11/15/96
22	Estimate ~~Consultants~~ Cost - Construction	11/18/96	12/12/96
23	Project Completed	12/13/96	12/16/96



Date: 6/5/96

Critical
Work Done
Noncritical
Progress
Milestone
Summary
Rolled Up

Hughes Associates, Inc.
Fire Science & Engineering

3610 Commerce Drive, Suite 817, Baltimore, MD 21227-1652 (410) 737-8677 FAX (410) 737-8688

June 24, 1996

Donald Hayward
The Port Authority of NY & NJ
One World Trade Center, Rm 1933
New York, NY 10048

Re: WTC — Smoke Management Evaluation Study for the World Trade Center Complex Excluding the Concourse and Plaza

Dear Mr. Hayward:

The team assembled to conduct the site investigations and tests, June 28, 29, 30, July 1 and 2, 1996 will consist of the following persons:

From Hughes Associates, Inc.

Harold E. Nelson	SSN 347-20-8215 — [illegible]
Lawrence A. McKenna	SSN 143-48-3555 — [illegible]
Daniel B. Szepesi	SSN 212-94-3100 — [illegible]
Ajay V. Prasad	SSN 086-52-8021 — [illegible]

From Dillon Consulting Engineers, Inc.

Michael E. Dillon	SSN 570-66-6934

[illegible] M.S. degree in fire protection

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Dear Mr. Hayward:

The team assembled to conduct the site investigations and tests, June 28, 29, 30, July 1 and 2, 1996 will consist of the following persons:

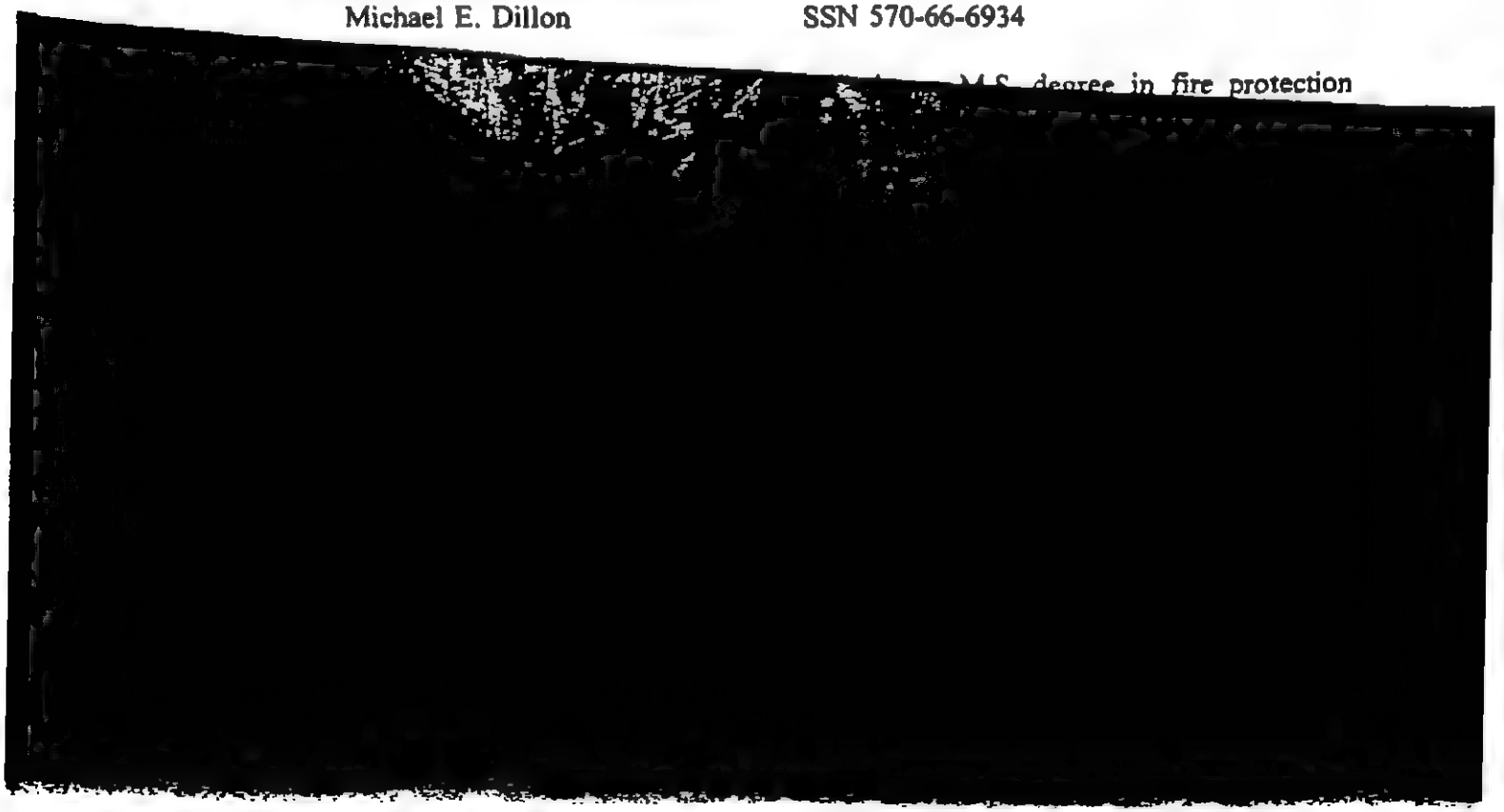
#135

From Hughes Associates, Inc.

Harold E. Nelson	SSN 347-20-8215 —	80130134 #135-228
Lawrence A. McKenna	SSN 143-48-3555 —	80130951
Daniel B. Szepesi	SSN 212-94-3100 —	80131576
Ajay V. Prasad	SSN 086-52-8021 —	80132000

From Dillon Consulting Engineers, Inc.

Michael E. Dillon	SSN 570-66-6934



M.S. degree in fire protection

NAMES, ETC.

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Don Hayward
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Dennis Malopolski

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Rm 1604

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Con $229
814 965-73

PROJECT SCHEDULE
June 24, 1996

SMOKE MANAGEMENT EVALUATION STUDY OF THE WORLD TRADE CENTER

PROJECT SCHEDULE S = Start; R = Report; X = Active Work

	July					August				Spetember				October					November				Dec.	
WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1. MEETINGS																								
a. Kick Off	X																							
b .First Progress Report						R																		
c. Second Progress Report																R								
d. Draft Final Report																		R						
e. Presentation of Final Report																				R				
2. PROJECT SCHEDULE																								
3. FIELD SURVEY & TESTING																								
a. Plans/Spec./P.A. Data	X																							
b. Flow/Leakage Tests	X																							
c. I.D. & measurement of paths	X																							
d. Recording/analyzing data		S	X	X	X	X	X	X	X	X	X													
4. DESIGN CRITERIA SUMMARY																								
a. Develop proposed criteria	S	X	X	X	X	X																		
b. Prelim. diagrams of potential paths		S	X	X	X	X																		
5. FIRE SCENARIOS																								
a. Office space scenarios	S	X	X	X	X	X	X	X	X	X	X													
b. Other spaces of concern.A49	S	X	X	X	X	X	X	X	X	X	X													
c. Progress report - Task 3, 4, & 5						R																		

PROJECT SCHEDULE June 24, 1996		SMOKE MANAGEMENT EVALUATION STUDY OF THE WORLD TRADE CENTER																							
6. Smoke Migration Analysis																									
a. Cataloging of leakage path types	S	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									
b. Compiling layout into CONTAM		S	X	X	X	X	X	X	X	X	X	X	X	X	X	X									
c. Inserting leakage paths in model			S	X	X	X	X	X	X	X	X	X	X	X	X	X									
d. Loading HVAC capabilities				S	X	X	X	X	X	X	X	X	X	X	X	X									
e. Assigning wind factors in model				S	X	X	X	X	X	X	X	X	X	X	X	X									
f. Developing Base model for proofing			S	X	X	X	X	X	X	X	X	X	X	X	X	X									
g. Adding fire scenarios to model					S	X	X	X	X	X	X	X	X	X	X	X									
h. Analyzing results v. criteria									S	X	X	X	X	X	X										
i. Iterations									S	X	X	X	X	X	X										
j. Analysis of impact											S	X	X	X	X	X									
k. Testing/analysis of alternatives					S	X	X	X	X	X	X	X	X	X	X	X									
l. Progress Report - Task 6												S	X	X	X	R									
7. Rec. Smoke Management Design																									
a. Stairways WTC 4 & WTC 5								S	X	X	X	X	X	X	X	X									
b. Stairways WTC 1 & WTC 2								S	X	X	X	X	X	X	X	X									
c. Zone Pressurization (by floors)								S	X	X	X	X	X	X	X	X									
d. Elevator pressurization								S	X	X	X	X	X	X	X	X									
e. Others suggested by the data developed										S	X	X	X	X	X	X									
8. Findings.																									
a. Draft Report				S	X	X	X	X	X	X	X	X	X	X	X	X	R								
b. Final Report													S	X	X	X	X	X							
c. Presentation of Final Report																			R						
9. Post Report Wrap-Up																				X	X	X	X		
Products																									
1. Report of Tasks, 3, 4 & 5				8/9/1996																					
2. Progress Report Smoke Migration Analysis				10/18/1996																					
3. Draft Report				11/1/96																					
4. Final Report				11/15/96																					

A Study of Evacuation Behavior in the World Trade Center Explosion

Yoshiyuki Yoshida
Takenaka Corporation, Tokyo, Japan

Abstract

This paper is an analysis of five interviews conducted after the World Trade Center explosion on February 26, 1993, in New York City. Five people who were among those evacuated from the towers reported their experiences. The testimonies were analyzed according to the number of evacuees, occupants' awareness and knowledge of the emergency, behavior until egress, behavior in stairways, reverse flow of evacuees, and time to egress. According to the study, characteristics of human behavior become apparent in mass and simultaneous egress.

Introduction

The interviews were conducted from April 10 to 18, 1993, by the Ministry of Construction in Japan. Five Japanese business people who worked in the World Trade Center towers were interviewed. They were among those forced to evacuate by the explosion on February 26, 1993. Though the testimonies concern only a part of the incident, they can help us recreate the World Trade Center's egress and fire safety features (see Figure 1). The author was one of the interviewers, and all names have been changed.

In the Parking Garage on the B3 Level

At the time of the explosion, Nagata, an office manager from the 90th floor in Tower 1 (North Tower), was in the parking lot on level B3.

"I came to a parking lot on the B3 level near Tower 2 (South Tower) to get a document in my car. Suddenly, as I was sitting on the seat, the car shook strongly, as if another car collided with it from behind. I saw floor slabs shaking furiously, and all the other cars were shaking, too. I heard an alarm. The lights turned off immediately. However, since car alarms in many cars activated and headlights flashed, the parking area wasn't completely dark. I searched for a stairway with the help of the car lights. The stairway I used might have been the one in Tower 2, which led me onto Liberty Street.

"To figure out what was happening, I reentered Tower 2 through a revolving door and went into the shopping mall, which was still lighted and open. About five minutes later, smoke came into the mall. On the way to the mall, I must have

Key words: egress, evacuation, human behavior, stack effect, World Trade Center

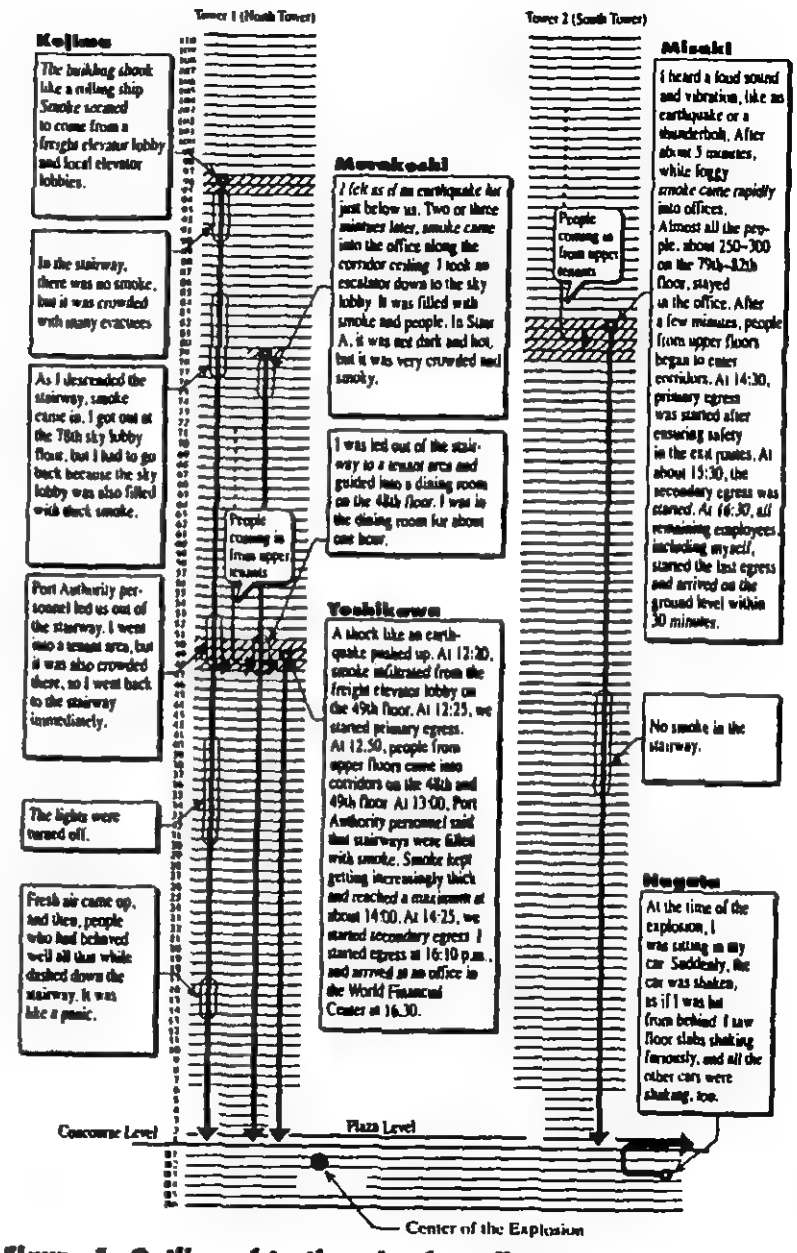

Figure 1. Outline of testimonies from five witnesses.

passed through the concourse of Tower 2. I'm not sure, however, whether there was smoke."

On the 95th Floor in Tower 1

Kojima, a vice president of Company A on the 95th, 96th, and half of the 85th floors, has a staff of nearly 500.

"After a meeting on Long Island," he said, "I drove to the World Trade Center and arrived at 11:45. Since the regular parking area on level B2 at the north side of Tower 1 was full, I had to drive to the other parking area at the south side of Tower 2 on the same floor."

On his way, Kojima passed the bomb that would soon detonate.

"I remember clearly that it was 11:55 when I entered the concourse in Tower 1. After awhile, perhaps at 12:00, I arrived at my office on the 95th floor and opened my lunch box. The tower began to shake loudly. The movement of the building was like a rolling ship. There was an uproar among employees.

"Although the lights turned off with the shock, power for computers was still supplied. I ordered people to save data before they lost power. When I opened a door to a corridor, thin smoke came in, and employees began to scream "fire" and "escape." Smoke seemed to come from the lobbies of a freight elevator and local elevators.

"I evacuated all the employees, except six Japanese employees who left after they finished storing things such as cash and travelers' checks in safe boxes. The time was perhaps 12:45. As smoke infiltrated into offices, visibility was down to nearly 10 yards. I conducted the remaining staff's escape. Then I locked the office doors and entered a stairway. The time was perhaps 13:30."

The primary egress start time of 12:45 and the secondary egress start time of 13:30 seem incorrect. The reason for this will be mentioned later.

"After the explosion, I never heard any announcement from the Port Authority or others. I entered a stairway with my briefcase and overcoat. In the stairway, it was light. There was no smoke, but it was crowded. However, people were calm and even congenial.

"As I descended the stairway several stories, smoke came in. When I opened an exit door, I found thicker smoke outside and people said, 'close the door.' The color of the smoke in the stairway was white, and visibility was 1 or 2 yards. I took my handkerchief and covered my nose and mouth."

It should be noted that there was no smoke when he entered the stairway. His comments also suggest that smoke came into the offices before it came through the stairways. Therefore, the primary smoke would have come into offices through the elevator shafts. After awhile, however, the stairway filled with smoke, driving the evacuees out.

"As we kept descending, I felt heat, moisture, and sweat. Overcoats and shoes were lying about on the steps. I also wanted to take off my jacket, but I couldn't

do it because I was in a dense crowd that was moving slowly. Because it was so hot, smoky, and crowded, I left the stairway at the 78th sky lobby floor. However, I had to get back into the stairway, because the sky lobby was also filled with thick smoke. At nearly the 50th floor, Port Authority personnel led us out of the stairway. I followed their orders and went into a tenant area, but I went immediately back to the stairway because that area was also crowded."

It is assumed that the area he entered was Company C.

"In spite of the crowd and smoke in the stairway, people were well-regulated. I saw a man tear his handkerchief and give the pieces to others to cover their noses and mouths. When a pregnant woman came down, we opened the way for her. We also opened the way for a disabled person on a heavy electrical wheelchair carried by several volunteers.

"At between the 40th and 30th floor, the lights in the stairway turned off, and people were strained and screaming. However, they did not panic. After about 30 minutes, firefighters came up and lighted the stairway with their flashlights. At about the 15th floor, fresh air came up, and then, people who had been calm dashed down the stairway . . . . It was like a panic. I entered the stairway at 13:30 and arrived at the ground level at 15:30. All in all, my egress took about two hours."

Although he said he left his office at 13:30, he must have started earlier. The NFPA report[1] puts the time the lights in the stairway went out at about 13:35—about 1 hour and 15 minutes after the detonation. The blackout occurred when Kojima was between the 30th and 40th floor. Since he entered the stairway on the 95th floor, he must have taken at least 30 minutes, or perhaps up to an hour, to descend 55 or 65 flights. Therefore, he might have entered the stairway at 13:00, at the latest, and he would have taken 2½ to 3 hours to descend the stairway.

"On the ground, my face was stained with soot around my nose and mouth. My clothes were also stained, from business suit to underwear."

On the 79th Floor in Tower 1

Murakoshi is president of a small company, Company B, on the 79th floor in Tower 1. The Vista Hotel is located just below his window, which means that he was just above the point of explosion. At the time, he was in his office with a coworker.

"It felt as if an earthquake hit just below us. As I looked down from a window, police cars and fire engines began to arrive, but I didn't know what was happening. There was no announcement of an emergency. Two or three minutes after the shock, smoke came into the office along a corridor ceiling. Immediately, I decided to escape and went down to the sky lobby on the 78th floor by escalator."

Considering that Murakoshi's office was on the 79th floor, the speed of smoke spread was remarkable, suggesting that smoke came up through express elevator

shafts. Since the corridor in front of Murakoshi's office is connected to the sky lobby by escalators, smoke could easily have come up to his office.

"The sky lobby was filled with smoke and people. I could not find Port Authority personnel. I tried to enter Stair C, but couldn't get into it because it was very crowded. So I entered Stair A on the opposite side . . . . In Stair A, it was not dark and hot, but it was very crowded and smoky."

Since Murakoshi entered the stairway earlier than Kojima, why was the stairway already filled with smoke? Smoke movement will be discussed later.

"I have never been seized with such a fear in my life as I was in the stairway," Murakoshi said. "After descending for some time, I was led out from the stairway to an area of Company C. Then, I was guided into a dining room on the 48th floor, where I felt safe. It might have been one hour from the start of egress. I saw that about 10 windows in the dining room had been broken."

Like Kojima, Murakoshi left the stairway and entered Company C.

"I stayed in the dining room. Sometime later, emergency personnel told me that it was safe to start egress, but I remained there because the stairway still seemed smoky. After awhile, I'm not sure when, I started egress again and arrived on the ground at 15:10. I think I spent about one hour in the dining room.

"As I look back on it now, I should not have escaped in such a hurry because the fire might not have expanded throughout the entire tower. The worst part was that there was no emergency announcement."

On the 48th to 50th Floors in Tower 1

Yoshikawa is a vice president of Company C, which occupies floors 48 to 50. He talked about the situation and referred to the company's official report.

"At 12:18, a shock like an earthquake came up from just below us. Immediately, lights at the north side of the 48th and 49th floors turned off, but those at the south side still worked. A man tried to contact the Port Authority with an emergency phone but could not get through.

"At 12:20, smoke infiltrated from the freight elevator lobby near a men's room on the 49th floor. Every section started egress preparation, which included storing important things in safe boxes. At 12:25, the primary egress for the operator-class staff was started. About 12:30, smoke became thicker in the corridors, while it remained thinner in the offices. We closed doors to shut off the smoke, but it would not stop. At 12:50, people from upper floors, led by Port Authority personnel, came into the corridors on the 48th and 49th floors. Their faces were stained with soot around their noses and mouths. The number of evacuees that came from offices on upper floors might have been more than 1,000. The corridor on the 49th floor was so crowded with people, it was motionless."

Both Kojima and Murakoshi were in the crowd that Yoshikawa described. It is significant that a substantial number of evacuees entered Company C.

"At 13:00," Yoshikawa continued, "Port Authority personnel told us that the

stairways were filled with smoke, that it was impossible to go lower than the 44th floor, and that we were not to break windows. At this time, we heard a radio announcement that the fire had been extinguished, and it was better to stay on the floor. However, smoke kept increasing and reached the maximum at about 14:00. We broke about 10 windows on the 48th floor . . . .

"At 14:00, lights on the south side of the floor shut down. At 14:25, smoke became thinner in the stairways than in the offices. Then the secondary egress group, which included everyone except 10 people in administrative posts, was started. Smoke thinned slowly in offices, and more rapidly in the stairways.

"At 15:10, firefighters came up, and at 15:30, police officers followed. At this time, the smoke in the offices thinned. At 16:00, three members started egress after confirming that there was no one left on the 48th, 49th, and 50th floors. We could have stayed in the office, but police officers forced us to get out, so we started to leave at 16:10 and arrived at an office in the World Financial Center at 16:30."

While in their offices, Company C employees kept telephone contact every half hour with a provisional office set up for the incident.

On the 79th to 82nd Floors in Tower 2

Misaki, a manager of Company D in Tower 2, talked about the situation and referred to his company's official report.

"I felt a big . . . vibration and [heard a big sound] such as an earthquake or . . . a thunderbolt. Immediately after the shock, lights turned off, and the computer system shut down on the west side of the floor. Elevators stopped, too, but telephones connected directly to the outside and some telephones through the PBX were still available.

"After about five minutes, white foggy smoke came rapidly into offices. Since there was almost no information about what was happening, I was busy organizing the staff. A man who was gathering information on the phone reported that it was not a fire but an explosion. People in the company called 911 and television stations to get information. A man called the Operations Control Center (OCC) but could get no answer. Another man in charge of emergency egress on the 80th floor called the Port Authority but could not contact it, either. It was most helpful, however, that we could use the phones.

"Almost all the people, about 250 to 300 on the 79th to 82nd floors, stayed in the office and followed directions. After a few minutes, people from . . . the upper floors began to enter the corridors. Because they appeared confused and seemed to cause unrest to the people in my office, the staff guided them into a room [away] from other people."

It should be noted that here in Tower 2, the same situation occurred as in Company C in Tower 1—evacuees overflowed the stairways into the tenant area.

"At about 13:50," Misaki continued, "power on the east side shut down. As

smoke spread from the 78th floor to upper floors, all of us escaped one by one, floor by floor, through a stairway in the tenant area. Then finally, at about 14:00, we escaped to the 82nd floor and waited for firefighters. At this time, we stopped working and decided to shift the job to a backup site in New Jersey—we were prepared for an emergency."

It is interesting that they kept working, or at least intended to do so.

"While we stayed on the 82nd floor, smoke became thicker, and a few people started to have difficulty breathing. We sealed stairway doors with wet towels. We also considered breaking windows, but stopped as advised by Port Authority personnel and police officers . . . .

"After awhile, we selected several young employees to ensure safe exit routes. They went down the stairways, and sometime later, reported by phone that it was safe. Then at 14:30, we started the primary egress. People who escaped at this time said that, because the stairway was lighted by firefighter's flashlights, they could go down easily and arrive at the ground level in nearly one hour.

"At about 15:30, we started secondary egress for two pregnant women and another with a cardiac disease who had been kept protected in the cleanest room in our office and attended to by office staff. At about 16:30, all remaining staff, including myself, started the last egress and arrived on the ground level in 30 minutes. We mainly used Stair B. Some staff used Stair A, but not Stair C because it was filled with smoke."

Estimating the Number of Evacuees

How many people were in the towers at the time of the explosion? According to the NFPA report, the World Trade Center has an average daily population of 150,000 people, which is made up of approximately 60,000 people who work there and another 90,000 business people and other visitors. However, these figures do not seem to indicate the number of explosion evacuees. The 90,000 visitors represent the total for the day, not necessarily the number in the building at one time. Furthermore, the figure of 150,000 is for the entire World Trade Center complex, including Towers 1 through 6 and Tower 7.

A better way to estimate the number of occupants in a single tower at the time of the explosion uses the following method. The total area of one tower is approximately 4,600,000 square feet. Assuming the efficiency of tenant areas is from 70 to 80% and 200 square feet per person, the total population will be from 16,100 to 18,400. Ten to 20% of these people could have been absent because they were working outside of their offices, on vacation, or sick. In addition, because the explosion occurred during lunchtime, 30 to 40% of the people could have been out for lunch. Consequently, the number of occupants in one tower at the time of explosion would vary from nearly 7,700 to 11,600. Visitors can be ignored because it was lunchtime.

Occupants' Awareness and Knowledge of the Emergency

In Tower 1, people in Companies A (95th to 96th floors), B (79th floor), and C (48th to 50th floors) heard and felt a shock that resembled an earthquake just below them. Even in Tower 2, away from the explosion, people in Company D (79th to 82nd floors) felt a vibration and heard a sound like an earthquake or thunderbolt.

Everyone in the towers realized it was an emergency because of the smoke that infiltrated a few minutes after the shock, not because of any announcement from a fire alarm voice communication system. Smoke did not come from offices, but from corridors next to lobbies of local and freight elevators.

No one could contact the OCC, but people tried to make contact with others outside the building to find out what was going on. Some telephones stopped working, but cellular phones and those that connected directly to the outside worked. People tried to contact not only emergency officials, but several head or allied offices of their companies. According to a fire department report,[2] because the emergency facilities received such a flood of calls, people in the tower should not have been able to make contact as easily as they did.

For the people who stayed in their offices, it must have been reassuring to be able to find out what was happening through telephones and radios.

Behavior Until Egress

Before leaving their offices, people in Companies A, C, and D conducted "preservation actions" such as saving computer data and storing important items in safe boxes. At Company A, the last evacuee locked the office doors.

When egress started, people appeared to be organized. Leaders in Companies A, C, and D gave priority to women and employees not in administrative posts. In Company D, people kept working until 14:00, and several young men were selected to assure a safe exit before the primary egress started.

People seemed to be faithful to their duties. It can be said that this response is proof of their coolness. However, people in an emergency seldom recognize the urgency and generally do not respond immediately to a hazard. Instead, they try to carry on their daily behaviors and follow the established rules until the circumstances become urgent. In addition, people in groups do not make decisions by themselves, but rather, wait for orders from a leader. Therefore, it can be said that they acted naturally.[3,4,5]

As a result, people who escaped earlier met a worse situation—prolonged and confused egress—than those who escaped later. However, the leaders who conducted the egress did what they thought was best based on very little information.

Behavior in Stairways

According to evacuees in the early stage—Kojima and Murakoshi in Tower 1—the crowd was so tightly packed that it restricted movement, and the smoke was so heavy that it stained their faces and clothes with soot. Kojima reported that the stairway was hot from the body heat of so many people. It is remarkable that people kept calm and even pleasant in spite of their difficulty in the stairways. It is, however, also interesting that people dashed as if in a panic when they met fresh air as they approached ground level. On the other hand, those who started to evacuate after 16:00—Yoshikawa of Company C and Misaki of Company D—escaped comparatively easily. There was almost no smoke or crowd, and the firefighters lighted the stairways.

The fact that the stairway was filled with heavy smoke when Murakoshi entered it, but was clear of smoke when Kojima entered later, raises a question about smoke movement. One explanation is that they used different stairways, but another hypothesis will be discussed later.

Both Murakoshi and Kojima testified that they got out of the stairway and entered Company C. Kojima returned to the stairway because Company C was too crowded, but Murakoshi stayed in the dining room for nearly an hour. It is interesting that such "reverse flow" is also reported at Company D on the 79th to 82nd floors of Tower 2.

Reverse Flow of Evacuees

The reverse flow of evacuees was reported in Companies C and D, but especially in Company C, where Yoshikawa said that more than 1,000 people had entered. Why did so many people have to "escape the stairway?" And why did Murakoshi find such heavy smoke in the stairway, when Kojima, who entered the stairway later, found none?

Since the World Trade Center Towers are extraordinarily tall, they have a high potential for stack effect. Normally, air-lock walls, windows, and revolving doors protect against this. The express and local elevator shafts would be where the stack effect would occur. Express elevators connect the concourse and sky lobbies, and the local elevators connect sky lobbies and every tenant floor (see Figure 2).

When the air-lock was broken, stack effect occurred in elevator shafts through openings around their doors and broken walls. Then, smoke blew up quickly in the sky lobbies on the 44th and 78th floors. The fact that Murakoshi entered the 78th sky lobby immediately after the explosion backs up this assumption. He recalled that the sky lobby was filled with smoke and people.

Smoke in the sky lobby spread over every tenant floor through local elevator shafts. Both Kojima and Yoshikawa said that smoke came up from elevator lobbies, not from the stairways. Eventually, smoke went up through express elevators and changed to local elevators on the sky lobby. The freight elevator shaft of

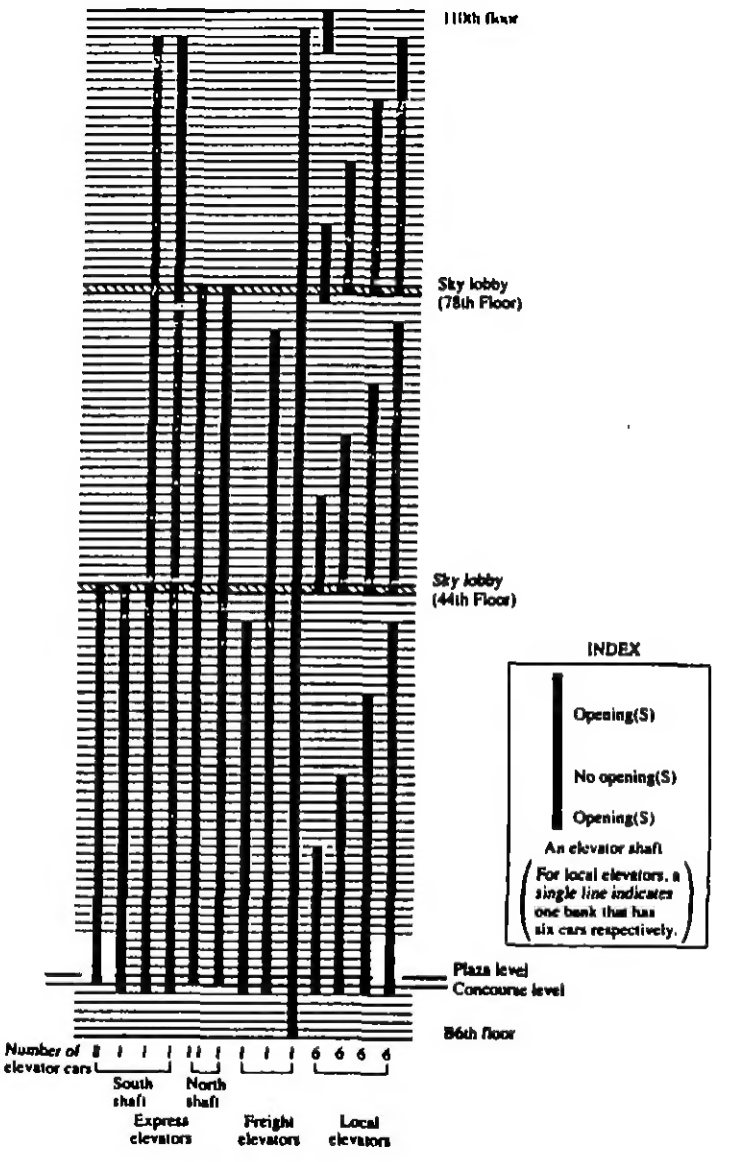

Figure 2. Elevator system and openings on its shafts.

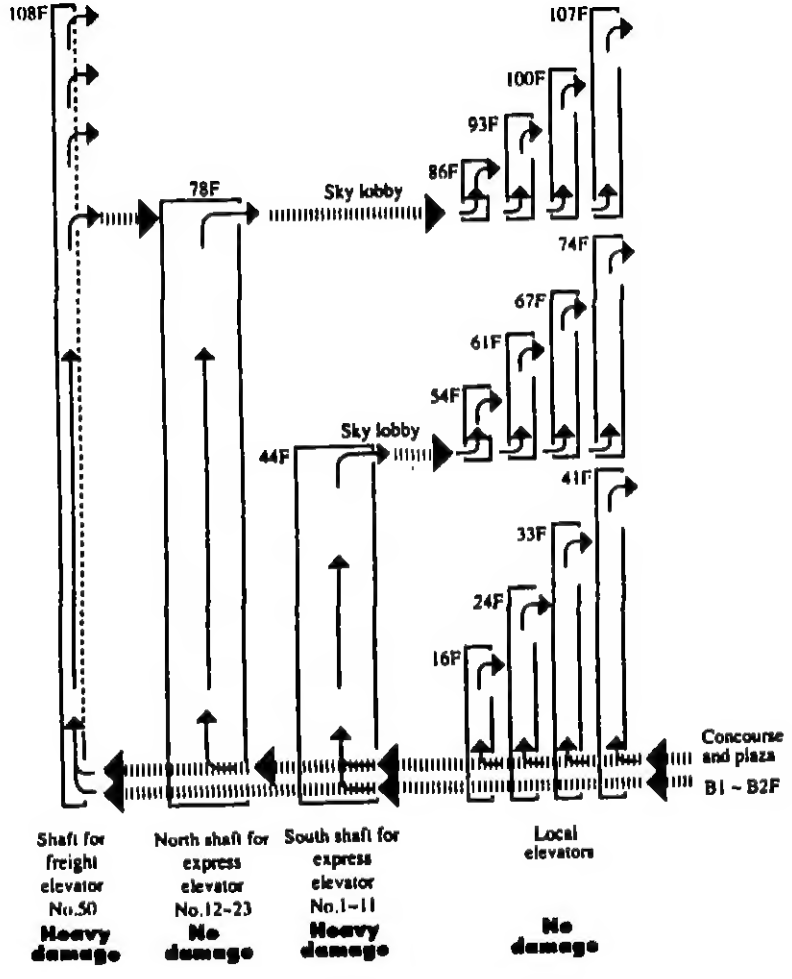

Figure 3. Assumed smoke route through elevator shafts and sky lobbies.

Car No. 50, with openings on every floor, should also be noted as a major smoke route in Tower 1, because its wall had heavy damage on the sublevels (see Figure 3).

Smoke in the sky lobby entered the stairways while the doors were kept open during egress. However, the smoke was interrupted by doors installed several floors above the sky lobbies where the stairway locations switched (see Figure 4). Smoke kept condensing in front of these doors until evacuees from upper floors opened them. When they were opened, smoke blew up in the stairways and drove the evacuees out (see Figure 5).

This answers the question of why there was no smoke when Kojima entered a stairway from the 95th floor, but there was smoke when Murakoshi entered earlier from the 78th floor. The upward rush of smoke in the stairways continued as long as the doors were opened, and it pushed people out into the tenant area.

Since the doors at the stairway transference points might be self-closing, the upward rush of smoke stopped when the evacuees disappeared. When Port Authority personnel said that it was impossible to go lower than the 44th floor in Company C, it probably meant that accumulated smoke rose when they opened the door at the transference point.

Since the same thing must have happened in the sky lobby on the 44th floor in Tower 1 and the sky lobby on the 78th floor in Tower 2, the reverse flow might have occurred on the floors above the sky lobbies, as well.

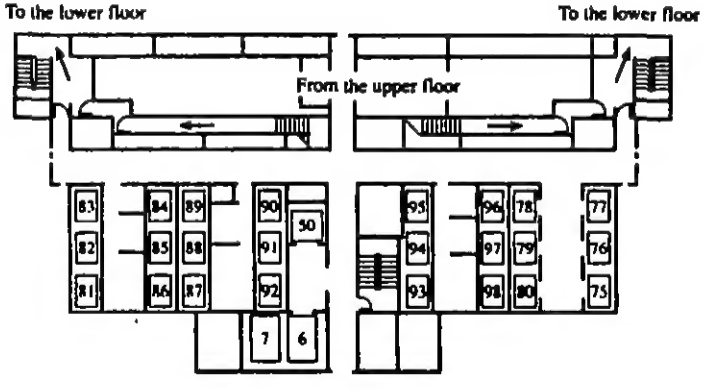

Figure 4. Transference of stairways on the 82nd floor.

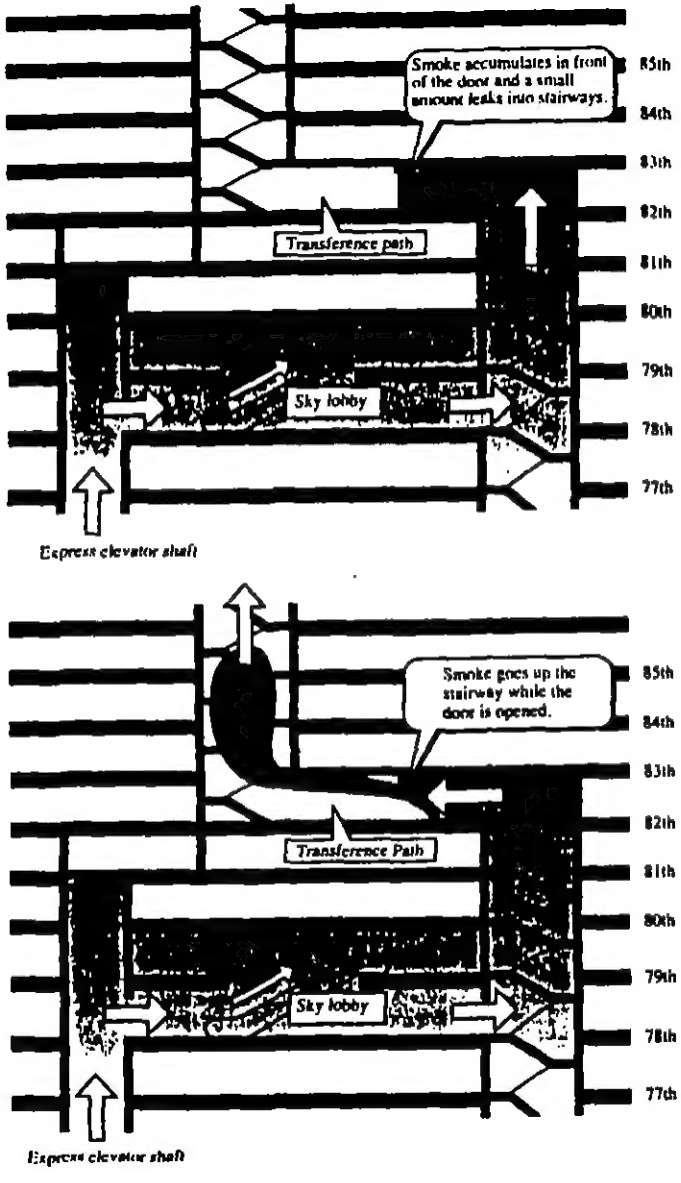

Figure 5. Assumed smoke movement in the stairway (modified section).

Time Used for Egress

Figure 6 is an egress timetable for the five people interviewed. In the table, Kojima's time is corrected based on the testimonies of other witnesses and the NFPA report.

Among the five business people, two escaped in the early stage. Murakoshi of Company B started egress immediately, and Kojima of Company A started egress at about 12:45. Murakoshi from the 78th floor required 2 hours and 50 minutes to get out, and Kojima from the 96th floor required about three hours for total

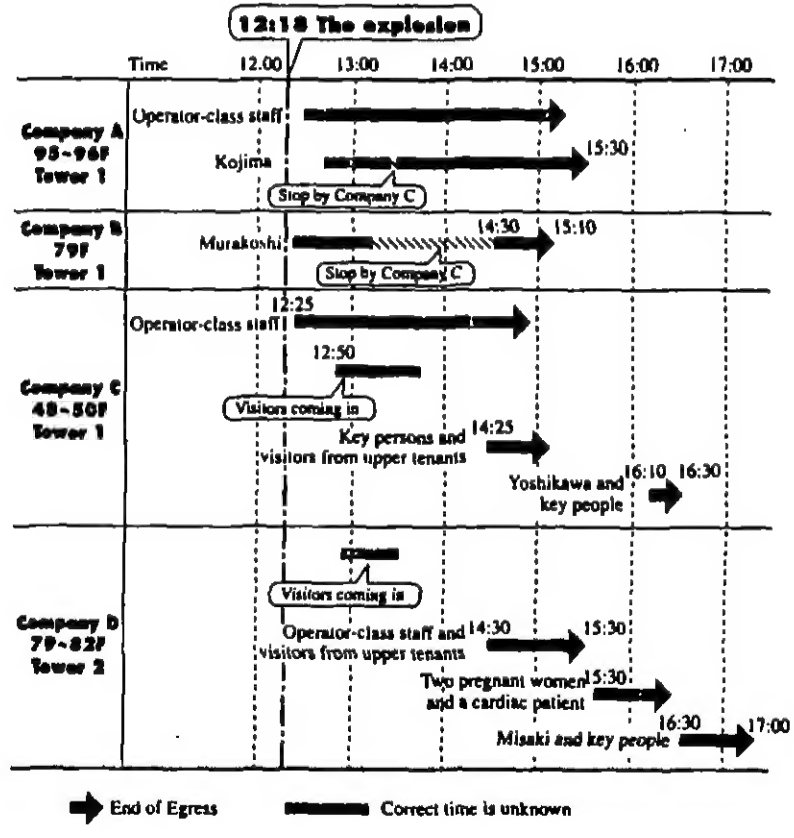

Figure 6. Egress time table of four witnesses.

egress. The net descending time for Murakoshi was about 2 hours because he stayed in Company C for about 1 hour.

On the other hand, almost all the people in Companies C and D, including those who came from upper floors stayed in the office and escaped later. In Company C, the egress was divided into three stages: the first immediately after the explosion, the second at 14:25, and the third at 16:10. People from upper floors were included in the second stage. In Company D, everyone stayed until 14:30, and then escaped in three stages at 14:30, 15:30, and 16:30.

Groups that started later took less time to get down the stairways. For instance, Yoshikawa's group started from the 48th (or 49th or 50th) floor at 16:10, and reached a meeting place in the World Financial Center at 16:30, so they took less than 20 minutes. Misaki's group took 30 minutes from the 82nd floor. Murakoshi started again from Company C at about 14:30 and took about 40 minutes.

Conclusions

This incident can be characterized by mass and simultaneous egress of people in a difficult situation. According to the analysis, the total number of evacuees was estimated to be from 7,700 to 11,600 people for each tower. This figure is lower than the numbers given in the NFPA report and in other news media. The occupants became aware of the emergency a few minutes after the shock when they noticed smoke. No announcement was made over the voice communication system. Before egress, people in many companies appeared to be organized, conducted preservation actions, gave priority to other employees, and followed leaders' directions. In the stairways, it was remarkable that people kept calm and pleasant in spite of the difficulty and confusion.

In this survey, we found a reverse flow of evacuees on the tenant floors above the sky lobbies on the 44th floor in Tower 1 and the 78th floor in Tower 2. The cause of the reverse flow was analyzed, and it was proposed that reverse flow might have occurred on the floors above the other sky lobbies, as well.

As for the time it took to escape, people who left earlier took about 2½ hours in the worst conditions—heavy smoke, dense crowd, and darkness—to reach the ground level, while people who started later took only 30 to 40 minutes. This shows the necessity of staggered—not simultaneous—egress, especially in mega-high-rise buildings. The communication and smoke control systems, especially for elevator shafts, are essential for staggered egress.

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References

1. Isner, Michael S., and Klem, Thomas J., "World Trade Center Explosion and Fire," Fire Investigation Report, National Fire Protection Association, February 26, 1993.

2. Fusco, Anthony L., "Report from Chief of Department," *Fire Engineering, Special Issue: World Trade Center Bombing*, 146 (1993), 12, pp. 9–23.

3. Kobayashi, Masami, and Horiuchi, Saburo, "Analysis of Occupant Behavior in an Office Building Under Fire, Part 2, Extraction of Behavior Patterns," *Transactions of the Architectural Institute of Japan*, No. 284 (October 1979).

4. Donald, Ian, and Canter, David, "Behavioral Aspects of the King's Cross Disaster," *Fires and Human Behavior*, second edition, David Fulton Publishers Ltd., (1990).

5. Sime, Jonathan, "The Concept of Panic," *Fires and Human Behavior*, second edition, David Fulton Publishers Ltd., 1990.